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# TEXTILE BALLISTIC PERFORMANCE

## (DATA BASE)

Final Technical Report

by


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Nylon and Kevlar textiles are examined for their performance against impact by a 1gm projectile, when subject to impact velocities up to 200 m/s. The textiles are of varying areal density, and of varying layer composition and their performance is examined theoretically and experimentally. The theoretical models have been previously developed and are the characteristic model, membrane finite element and a multilayer finite element; the experimental /cont'd.

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It was quickly found that the theoretical models favoured nylon over Kevlar for ballistic performance, whereas experimentally Kevlar is superior. It is also shown that the deformation process is correctly modelled and this then suggests that the fracture criterion must be reconsidered; possible fracture mechanisms to be included in textile failure criterion are stated for future consideration.

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## ABSTRACT

Nylon and Kevlar textiles are examined for their performance against impact by a 1gm projectile, when subject to impact velocities up to 2000 m/s. The textiles are of varying areal density, and of varying layer composition and their performance is examined theoretically and experimentally. The theoretical models have been previously developed and are the characteristic model, membrane finite element and a multilayer finite element; the experimental facility had also been previously established and this report is aimed at correlating the experimental and theoretical facilities and to establish a data base of results.

It was quickly found that the theoretical models favoured nylon over Kevlar for ballistic performance, whereas experimentally Kevlar is superior. It is also shown that the deformation process is correctly modelled and this then suggests that the fracture criterion must be reconsidered; possible fracture mechanisms to be included in textile failure criterion are stated for future consideration.



**Key words.**

Textile, Ballistic, Impact, Kevlar, Nylon, Finite element, Characteristics, Failure, multilayer, weave (woven).

## INTRODUCTION

This report uses previously established computational (ref,1,2,3,4) and experimental (ref.5) facilities at UMIST to generate a data bank for the behaviour of synthetic fibre textiles against ballistic impact.

The basic computational procedures used are firstly the method of characteristics which uses the propagational aspects in yarns to model the propagation of signals in yarn structure, namely textiles and secondly the finite element method which segments the plane of the textile into small elements and uses the principle of least action and the energy quantities to develope equations of motion for the element corners. This method is more appropriate for the detail of yarn crimp and for examining viscoelastic effects. The finite element method generates two codes, firstly the named membrane model which properly accounts for crimp and the multilayer-model which accounts for stacked textiles forming a layered structure.

The data basic was established using the following variable parameters.

i) ballistic parameters (impact velocity, projectile mass).
ii) Cómponent parameters (yarn stress strain behaviour)
iii) panel configuration (area density)
iv) structure parameters (layer composition)

The experimental facilities previously developed consist of a cartridge gun used to launch a 1gm projectile, .22" cylindrical projectile. The impact velocity, and if penetration occurs, the exit velocity of the projectile can be measured, it is therefore possible to calculate the $V_{50}$ or the energy absorption. In addition a multiflash photographic system has been developed in order to study the projectile deceleration dynamics and the configuration of the fabric during impact.

## THE COMPUTATIONAL INVESTIGATION

The computer experiments were conducted on a bank of launch and textile data, for Kevlar and nylon; this data is summarised in Tables 1a, 1b and the three computer models drew on this data to yield fabric behaviour with time. From this the projectile kinematics (kinetic energy, velocity) and fabric deformation (indentation, strain, strain energy) are extracted and ultimately used to deduce the fabric survival or integribility and ballistic resistance. The results are presented in a following section.

BALLISTIC RESISTANCE OF SYNTHETIC CLOTH

Kevlar breaking strain=0.032
projectile mass=1gm.

| Case No. | Model | Area den. gm./m.sq. | Impact vel m/s | Imp. energy joules | Exit vel. m/s | Res. energy joules | Contact time microsec. | Max. strain | % Energy abs. | % Energy left |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | characteristics | 400 | 500 | 125 | 496 | 123.01 | 5 | .032 | 1.59 | 98.41 |
| 2 | characteristics | 400 | 1000 | 500 | 998 | 498.00 | 2 | .032 | .40 | 99.60 |
| 3 | membrane | 400 | 1000 | 500 | 999 | 499.00 | 1.2 | .032 | .20 | 99.80 |
| 4 | multi(3)-layer | 400 | 1000 | 500 | 991 | 491.04 | 4 | .032 | 1.79 | 98.21 |
| 5 | characteristics | 400 | 1500 | 1125 | 1498 | 1122.00 | 1.4 | .032 | .27 | 99.73 |
| 6 | characteristics | 400 | 2000 | 2000 | 1999 | 1998.00 | 1 | .032 | .10 | 99.90 |
| 7 | membrane | 400 | 2000 | 2000 | 1999 | 1998.00 | .5 | .032 | .10 | 99.90 |
| 8 | multi(3)-layer | 400 | 2000 | 2000 | 1999 | 1998.00 | 2 | .032 | .10 | 99.90 |
| 9 | characteristics | 100 | 500 | 125 | 499 | 124.50 | 4 | .032 | .40 | 99.60 |
| 10 | characteristics | 500 | 500 | 125 | 496 | 123.01 | 4 | .032 | 1.59 | 98.41 |
| 11 | characteristics | 1000 | 500 | 125 | 450 | 101.25 | 10 | .032 | 19.00 | 81.00 |
| 12 | membrane | 1000 | 500 | 125 | 385 | 74.11 | 18 | .032 | 40.71 | 59.29 |
| 13 | multi(3)-layer | 1000 | 500 | 125 | 483 | 116.64 | 10 | .032 | 6.68 | 93.32 |
| 14 | characteristics | 1500 | 500 | 125 | 275 | 37.81 | 26 | .032 | 69.75 | 30.25 |
| 15 | characteristics | 2000 | 500 | 125 | 0 | .00 | 130 | .029 | 100.00 | .00 |
| 16 | membrane | 2000 | 500 | 125 | 0 | .00 | 66 | .024 | 100.00 | .00 |
| 17 | multi(3)-layer | 2000 | 500 | 125 | 487 | 118.58 | 10 | .032 | 5.13 | 94.87 |
| 18 | membrane | 3000 | 500 | 125 | 0 | .00 | 65 | .022 | 100.00 | .00 |
| 19 | multi(3)-layer | 3000 | 500 | 125 | 497 | 123.50 | 9 | .032 | 1.20 | 98.80 |
| 20 | membrane | 4000 | 500 | 125 | 0 | .00 | 63 | .021 | 100.00 | .00 |
| 21 | multi(3)-layer | 4000 | 500 | 125 | 497 | 123.50 | 9 | .032 | 1.20 | 98.80 |
| 22 | membrane | 1158 | 150 | 11.25 | 0 | .00 | 108 | .011 | 100.00 | .00 |

Table 1a

BALLISTIC RESISTANCE OF SYNTHETIC CLOTH

Nylon-a   breaking strain=0.24
projectile mass=1gm.

| Case No. | Model | Area den. gm./m.sq. | Impact vel m/s | Imp. energy joules | Exit vel. m/s | Res. energy joules | Contact time microsec. | Max. strain | % Energy abs. | % Energy left |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | characteristics | 400 | 100 | 5 | 0 | .00 | 245 | .146 | 100.00 | .00 |
| 2 | characteristics | 400 | 300 | 45 | 260 | 33.80 | 35 | .24 | 24.89 | 75.11 |
| 3 | characteristics | 400 | 400 | 80 | 379 | 71.82 | n.a. | .24 | 10.22 | 89.78 |
| 4 | characteristics | 400 | 500 | 125 | 485 | 117.61 | 16 | .24 | 5.91 | 94.09 |
| 5 | characteristics | 400 | 1000 | 500 | 994 | 494.02 | 7 | .24 | 1.20 | 98.80 |
| 6 | membrane | 400 | 1000 | 500 | 998 | 498.00 | 3 | .24 | .40 | 99.60 |
| 7 | multi (3)-layer | 400 | 1000 | 500 | 152 | 11.55 | 2.5 | .24 | 97.69 | 2.31 |
| 8 | characteristics | 400 | 2000 | 2000 | 1997 | 1994.00 | 3.8 | .24 | .30 | 99.70 |
| 9 | membrane | 400 | 2000 | 2000 | 1999 | 1998.00 | 1.5 | .24 | .10 | 99.90 |
| 10 | multi (3)-layer | 400 | 2000 | 2000 | 220 | 24.20 | 6 | .24 | 98.79 | 1.21 |
| 11 | characteristics | 100 | 500 | 125 | 497 | 123.50 | 14 | .24 | 1.20 | 98.80 |
| 12 | characteristics | 200 | 500 | 125 | 492 | 121.03 | n.a. | .24 | 3.17 | 96.83 |
| 13 | characteristics | 500 | 500 | 125 | 480 | 115.20 | 16 | .24 | 7.84 | 92.16 |
| 14 | characteristics | 600 | 500 | 125 | 464 | 107.65 | n.a. | .24 | 13.88 | 86.12 |
| 15 | characteristics | 800 | 500 | 125 | 433 | 93.74 | n.a. | .24 | 25.00 | 75.00 |
| 16 | characteristics | 1000 | 500 | 125 | 350 | 61.25 | 40 | .24 | 51.00 | 49.00 |
| 17 | membrane | 1000 | 500 | 125 | 390 | 76.05 | 24 | .24 | 39.16 | 60.84 |
| 18 | multi (3)-layer | 1000 | 500 | 125 | 153 | 11.70 | 57 | .24 | 90.64 | 9.36 |
| 19 | characteristics | 1100 | 500 | 125 | 0 | .00 | n.a. | n.a. | 100.00 | .00 |
| 20 | characteristics | 1500 | 500 | 125 | 0 | .00 | 130 | .19 | 100.00 | .00 |
| 21 | characteristics | 2000 | 500 | 125 | 0 | .00 | 135 | .17 | 100.00 | .00 |
| 22 | membrane | 2000 | 500 | 125 | 0 | .00 | 175 | .196 | 100.00 | .00 |
| 23 | multi (3)-layer | 2000 | 500 | 125 | 487 | 118.58 | 25 | .24 | 5.13 | 94.87 |
| 24 | membrane | 3000 | 500 | 125 | 0 | .00 | 134 | .187 | 100.00 | .00 |
| 25 | multi (3)-layer | 3000 | 500 | 125 | 490 | 120.05 | 25 | .24 | 3.96 | 96.04 |
| 26 | membrane | 4000 | 500 | 125 | 0 | .00 | 86 | .184 | 100.00 | .00 |
| 27 | multi (3)-layer | 4000 | 500 | 125 | 491 | 120.54 | 14 | .24 | 3.57 | 96.43 |
| 28 | characteristics | 100 | 150 | 11.25 | 0 | .00 | n.a. | n.a. | 100.00 | .00 |
| 29 | characteristics | 100 | 300 | 45 | 292 | 42.63 | n.a. | .24 | 5.26 | 94.74 |
| 30 | characteristics | 200 | 100 | 5 | 0 | .00 | n.a. | n.a. | 100.00 | .00 |
| 31 | characteristics | 800 | 400 | 80 | 0 | .00 | n.a. | n.a. | 100.00 | .00 |
| 32 | characteristics | 800 | 1500 | 1125 | 1462 | 1068.72 | n.a. | .24 | 5.00 | 95.00 |
| 33 | membrane | 1158 | 150 | 11.25 | 0 | .00 | 263 | .067 | 100.00 | .00 |
| 34 | characteristics | 1500 | 700 | 245 | 0 | .00 | n.a. | .24 | 100.00 | .00 |
| 35 | characteristics | 1500 | 1000 | 500 | 949 | 450.30 | n.a. | .24 | 9.94 | 90.06 |
| 36 | characteristics | 1500 | 1500 | 1125 | 1470 | 1080.45 | n.a. | .24 | 3.96 | 96.04 |
| 37 | characteristics | 2000 | 1000 | 500 | 0 | .00 | n.a. | n.a. | 100.00 | .00 |

Table 1b

THE EXPERIMENTAL INVESTIGATION

The experimental program was designed to obtain data on the $V_{50}$ (the velocity at which 50% of projectiles are defeated) and the energy absorption of multilayer nylon and Kevlar fabrics. In order that the experimental work should be as directly comparable to the computer models the projectile was chosen to be a blunt nosed cylinder rather than the chisel nosed fragment simulator more generally used. In additon the fabric has a fixed boundary in the computational model and is likewise clamped in the experimental case.

Apart from the $V_{50}$ and the energy absorbtion there are secondary output parameters concerned with the mechanism of the projectile fabric interaction . Examples of these parameters are

i) projectile decleration and the applied force;
ii) stress and strain distribution within the fabric;
iii) the position of the transverse wave;
iv) the time to failure.

It is of great interest to compare these outputs with observations of actual impact either to confirm computer prediction or in order to indicate where improvements in the simulation can be made.

There is currently a lack of published data on woven fabrics in this area. Notable exceptions are the independent work of Maheux[6], Roylance[7] and Morrison[8]. Roylance has observed photographically the transverse impact of a single layer of nylon fabric at velocities between 116 and 537 m/sec and provides data on the position of the transverse wave (cone radius) as a function of time for the lowest impact velocity.

Morrison has applied multi-flash silhouette photography to observed the response to impact of Kevlar fabrics incorporated in composite structures. These results have been compared to that of the fabric alone. Morrison uses data from single layer impact to determine the development of the pyramid deformation with time, and goes on to predict the partition of energy within the fabric during impact.

The aim of the present work was to extend this work to produce i) directly comparable results between Kevlar and nylon, and ii) information on the effect of the number of layers on the above mentioned parameters.

The above listed output parameters cannot all be measured either easily or directly. It was therefore decided that the current work should concentrate on the parameters which

could be measured photographically. These are :

i) the position of the pyramid apex as a function of time;
ii) the position of the transverse wave front, also a function of time;
iii) the time to failure.

The first parameter approximates to the projectile position. From these results the apex velocity and the transverse wave velocity can be calculated.

For the purpose of the present experimental work, two experimental variables were chosen, namely :

i) the area density of the multi-layered fabric;
ii) The fabric material.

In terms of end use the aim is always to optimise the latter in order to minimise the former.

## EXPERIMENTAL METHOD

Multi-layered samples were prepared such that the overall fabric weight was as close as possible to 1000, 2000, 3000 and 4000 g $m^{-2}$.

One Kevlar (351 g $m^{-2}$) and one nylon (241 g $m^{-2}$) fabric were tested. The nominal impact velocity was 500m $s^{-1}$.

The test method was as follows :-

An opaque screen was illuminated by a series of three light flashes of short duration. A still camera was located facing the screen. The camera was aimed along the plane of the back surface of the fabric at right angles to the direction of flight of the projectile. The camera was opened in a dark room and the lights were triggered by a circuit breaker just before impact. The actual times of each flash were recorded as a trace of light intensity against time on a transient recorder using a photodiode. The actual times of the flashes were found to differ from the times set on the delay box. This was attributed to delays inherent in the lights. The aim was to provide data at 10 s internals and also at 20$\mu$s or 40$\mu$s interval if penetration did not occur before the last flash.

## EXPERIMENTAL RESULTS

Typical photographs obtained by the above method are shown in figures 6a, b. In figure 6a the silhouette of the pyramid of deformation is shown at approximately 10, 20, 30 and 40 $\mu s$ after impact. Figure 6a (A to G) are nylon of nominal area density of 2000, 3000 and 4000 g $m^{-2}$ respectively, whilst D,E,F,G shows corresponding photographs of Kevlar.

No results were obtained for nylon at 1000 g $m^{-2}$ as penetration occurred too quickly after impact, and as will be explained below, at least two images are required in order to normalise results.

In figure 6b similar photographs of penetration are displayed; here, however, the deformations are shown up to the time of penetration, if this occurs.

All the multi-flash photographs are shown to the same scale. The minor divisions in the scale were of the order of millimeters, and the observed deformations were of the order of centimetres.

From these photographs and others the following were determined:

i) the pyramid height above the surface of the last layer (h),

ii) The distance between the left and right transverse wave front (D)

The time measured by the experiment was the time after the triggering of the electronic system by the projectile. Due to minor variations in impact velocity and also because of the change in the position of the last fabric layer due to variations in the sample thickness, results from different tests on different samples count not be immediately compared. In order to overcome this problem the measured times normalised such that the instant of first movement of the last layer was equal to $t_0$. This was accomplished by assuming an approximate constant velocity of apex, between the times of the first two light falshes (giving results $h_1$, $t_1$ and $h_2$, $t_2$). The normalised time $t_n$ was for any time t was found by

$$t_n = t + K$$

where $$K = t_1 - \frac{h_1(t_1 - t_2)}{(h_1 - h_2)}$$

The results for nylon and Kevlar are shown as plots of pyramid height v time in figures 6 c, e respectively.

No measurable deceleration was seen for the nylon data so the data points were statistically fitted to a straight line. It is not, however, assumed that no decelleration occurs, just that the decelleration is too small to be observable. Indeed, table 2

| Area Density ($g\ m^{-2}$) | Velocity ($m\ s^{-1}$) |
|---|---|
| 1928 | 382 |
| 2892 | 341 |
| 4097 | 277 |

TABLE 2

shows the average velocity of the apex during the observable projectile-fabric interation. This shows a reduction in mean interation velocity with increased area-density.

In contrast to the nylon data the Kevlar curves are concave downward reflecting an observable decelleration.

In both figures 6c,d,e,f, the cut off of the curve indicates that penetration occurs. No cut-off is observed for the 3861 $g\ m^{-2}$ Kevlar as penetration did not occur.

Figures 6g, h are plots of the distance of the transverse wave from the centre of impact (D/2) against time. There are no theoretical curve fits available but the plots are included for the sake of completeness.

This distance is measured along the warp direction such that the distance D corresponds to the pyramid diagonal. As before the nylon data has been fitted to straight lines. The similarity between figures either 6c and 6h suggests a linear relation between the pyramid height and width of the base. Figure 6i shows that this is indeed the case for both nylon and Kevlar. The ratio between the base and height being greater for Kevlar. There are also small differences in this relation dependent on the number of layers.

CONCLUSION AND DISCUSSION OF COMPUTATIONAL RESULTS.

The numerical results predict that nylon is better than Kevlar, which is in contradiction to experiments.

Three possible explanations surface

1. The analysis and computation is in error
2. The fabric properties are wrong
3. The failure criteria is incorrect.

The first two explanations seem unlikely in view of the agreement observed in Figures 6 c,d,e,f. Significant discrepancy is obvious not in the curve, but in the ending of the curve, namely the break point which is delayed in the computation model beyond the experimental results. The exception to this is the lower area density Kevlar textiles ($<1000$ g/m$^2$), when the computation and experiments are in quite good agreement.

The probable cause for the lack of agreement, is the definition of failure criteria. Kevlar fibres have been assumed to break at 0.032 strain and nylon at 0.24 strain. These are the quoted static fibre strain values and have been incorporated as a textile failure criteria (including the effect of crimp). These criteria will have to be re-evaluated in the light of the above, and it would appear that other effects beside straight tension failure of fibres are present when the textile fails.

They can be

a) early fibre failure due to strain rate (Viscoelastic)
b) premature failure in nylon due to local heating
c) cutting
d) bending, due to decrimping and flexure

for fibre failure and

e) accentuated stretch due to structure bending
f) yarn opening to allow projectile to proceed
g) fibre finishes to inhibit load equalisation

for the textile 'failure'.

Obviously these questions cannot be answered here but do suggest the need for a more detailed study of the localised phenomenon. It is suggested here that since fibre rate behaviours are known point (a) can be considered in an iterative or empirical manner. Also the correlation of experimental and computation results can be used to give a

measure of the fibre failure criteria when used in a structure , at high strain rates and against localised impact. This correlation and reverse criterion estimates were shown in the Appendix.

In conclusion it follows that

a) fibre tensile strength as obtained in a static test is of little use as a criterion for these fibres when used in a structure, at high rates of straining and in a localised impact.

b) the fibres need to be stiff and light (favouring Kevlar) so that as much of the textile structure is effective in the impact as possible (large cone area).

c) the fibre should be rough to give forth good fibre to fibre contact and thus sharing the impact over the structure and secondly to resist the opening force which is presented during impact especially by ogival or pointed projectiles.

d) they should be of low tex so that their flexure in crimp and in the impact process does not give rise to much higher strains (from bending).

e) consideration should be given to the effects of thermodynamic energy and how temperature rise influences stiffness.

f) resistance to cutting and crushing by the projectile must be considered again in the light of the above lack of agreement in the terminal phase between experimental observation and computer models based upon static tensile fibre strength.

## COMPUTATIONAL RESULTS

The three models used in predicting the performance of ballistic textiles are as follows :

a) The characteristics model uses the yarn material properties (mass and stiffness) and the yarn direction to determine the propagation of signals through the textile; there is no crimp or thickness modelling and it expected that for fast events this model would be quite accurate.

b) the membrane model which, based upon finite element theory can account in detail for the yarn path though the textile (crimp); however the model since it uses finite element theory cannot usefully predict high speed events since stress wave propagation is not accurately accounted for.

c) The multi-layer (finite element) model accounts for the layers (in this case, three) which are stacked together and can relatively slide and individually fail; because the structure thickness is now included this model should work well at lower speeds since at higher speeds the contacting layer can deform and indeed fail before the other layers have even started to move. This model would be used for thick structures with bending stiffness at lower velocities.

These models have been run for nylon and Kevlar for a series of impact velocities and fabric weights. The accompanying tables 1a and 1b summarise the fabric performance by considering exit velocity (and its derivative, residual energy, energy absorption) contact time (to break or stop) and the maximum strain encountered in the fibres.

The results of the computational models are presented in the following manner for both nylon A and Kevlar.

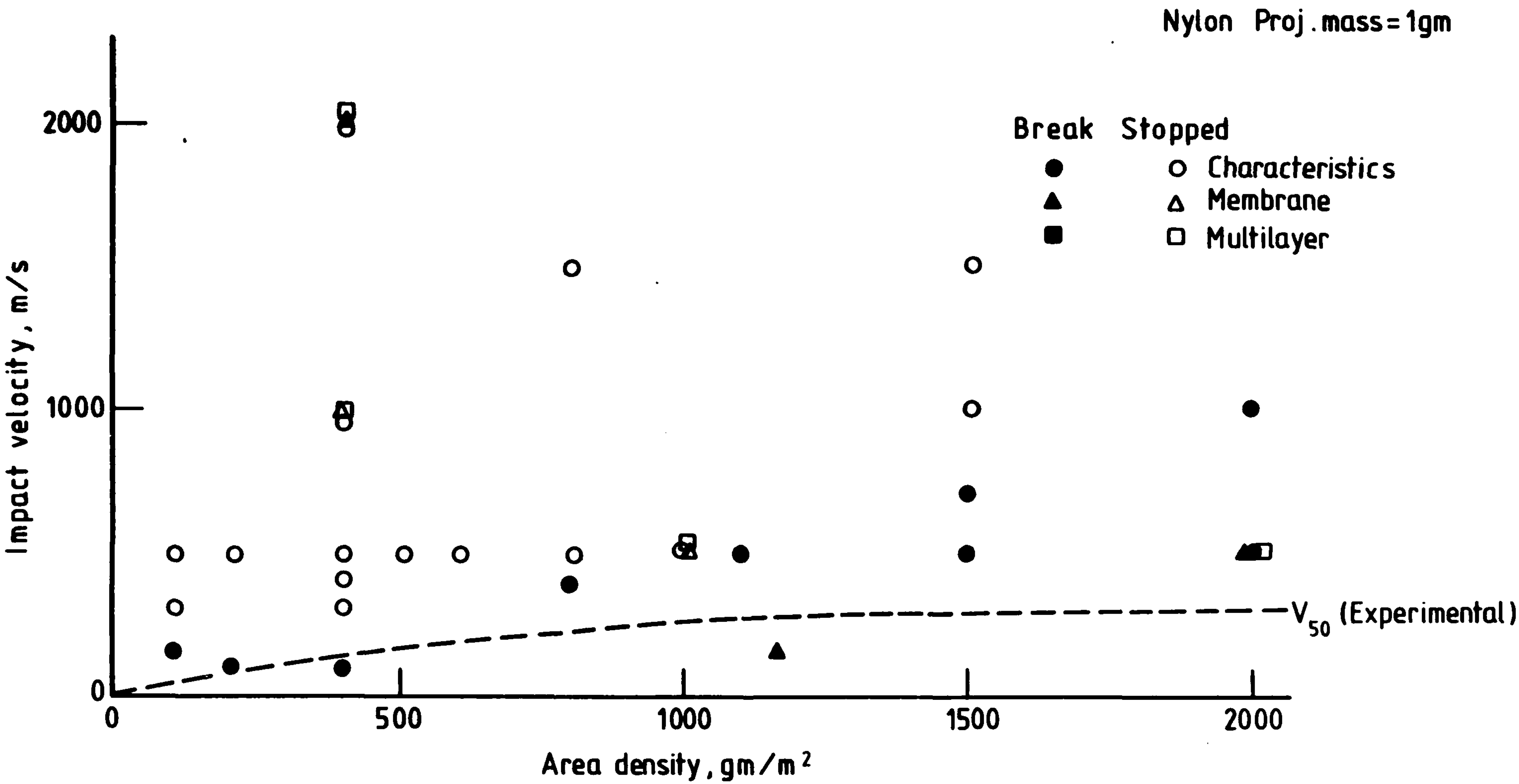
Firstly a carpet plot Fig.1a,b axes being impact velocity and area density; on these plots each case is entered, a point indicating that the projectile is stopped and a cross indicates that the fabric has failed. Also shown is the divide between stopping and penetration as estimated from a fit to existing experimental data.

Generally it is seen that the computer predictions give an upper value for the necessary impact velocities for a given textile structure (area density); it is also seen that more data is needed in the vicinity of the experimental data fit for the multilayer model since every prediction resulted in textile failure. This indeed may be the better model to use, although initially it was not thought to be as accurate as the characteristic or membrane models.

Without exception each prediction showed that nylon performed better than Kevlar from the point of stopping; however in comparable cases when both materials stopped the projectile Kevlar stopped it quicker (more deceleration). This is a consequence of the fact that Kevlar is stiffer and breaks at lower strain. Thus the energy absorbed may be less in the breaking cases, but in the stopping case the stiffness gives a faster arrest.

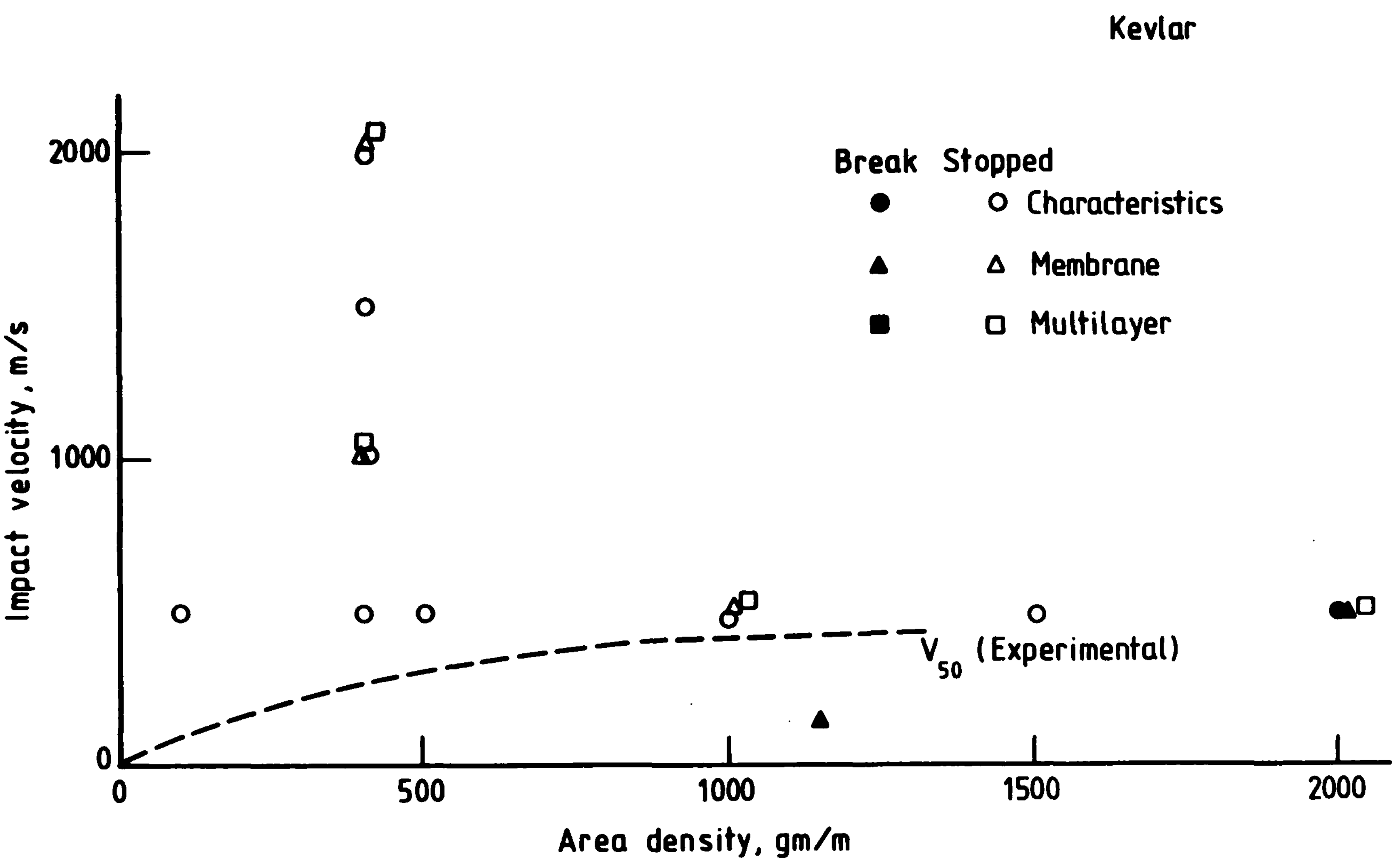
The divide between the break and stopping cases (crosses and dots) give a curve for the extraction of the $V_{50}$ against area density.

The figures 1c,d show the extrapolation of $V_{50}$ against area density using interpolation of the latter graphs.



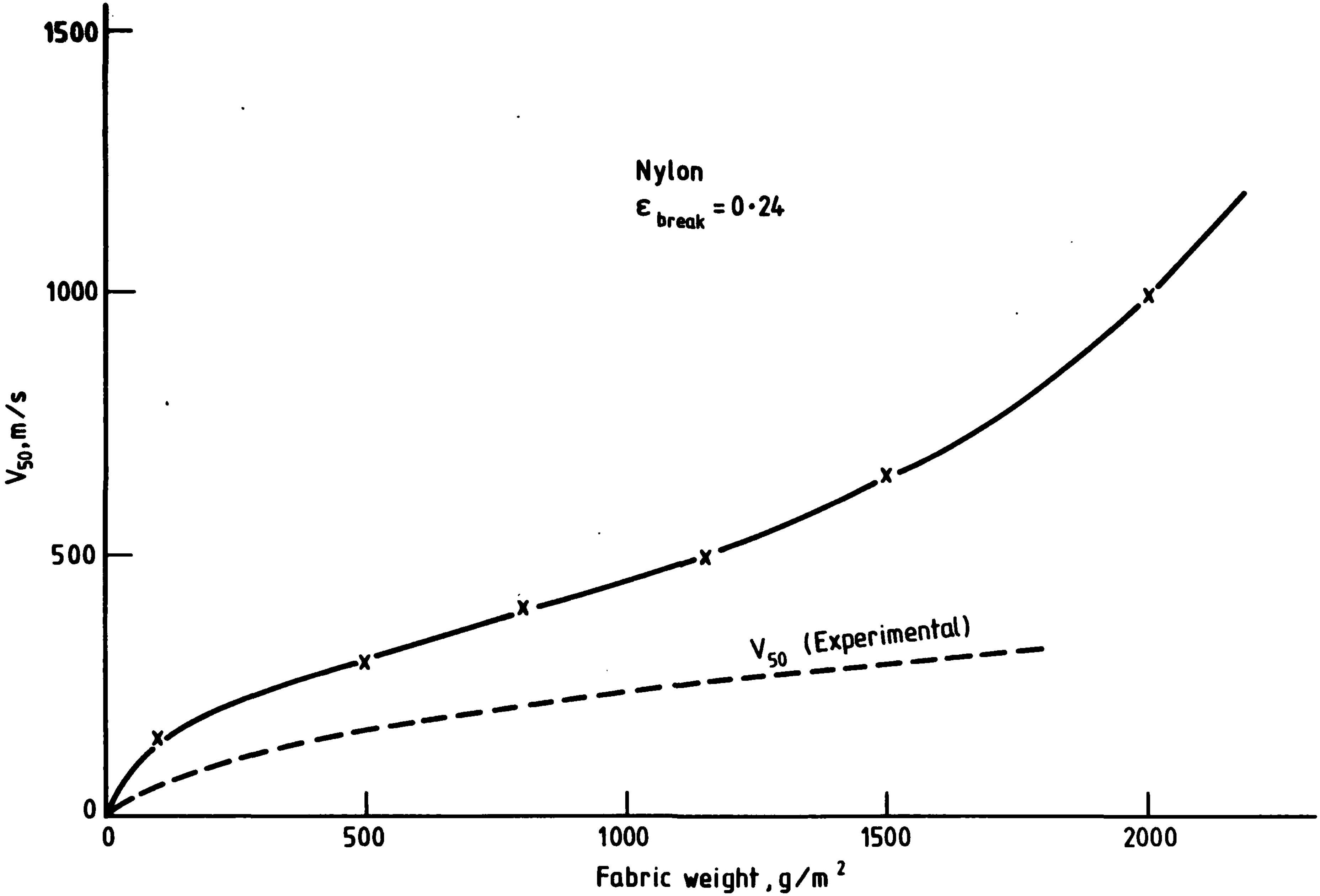

Breaking map

Fig. 1a




Breaking map

Fig. 1b




$V_{50}$ v Fabric weight

Fig. 1c

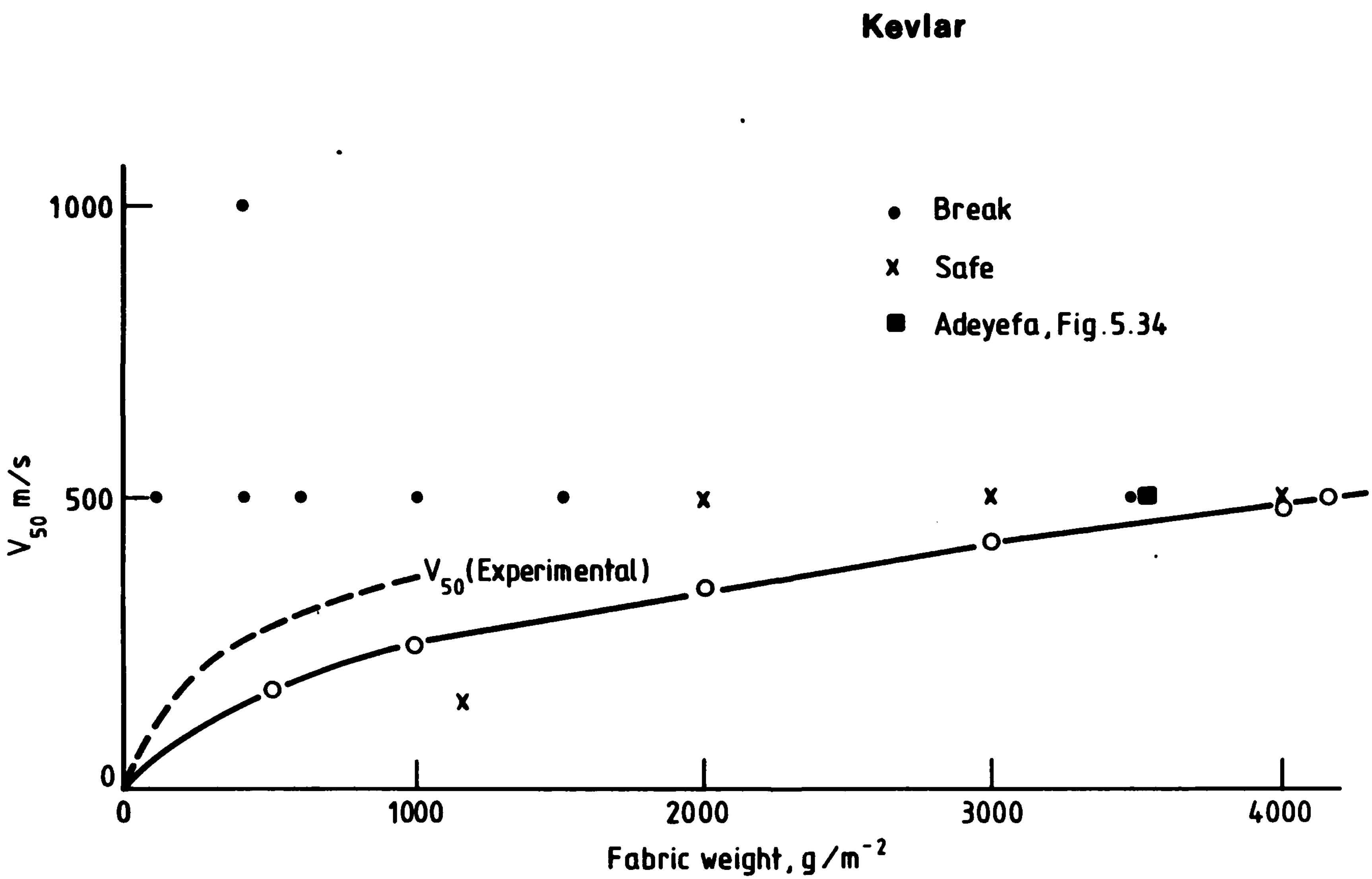
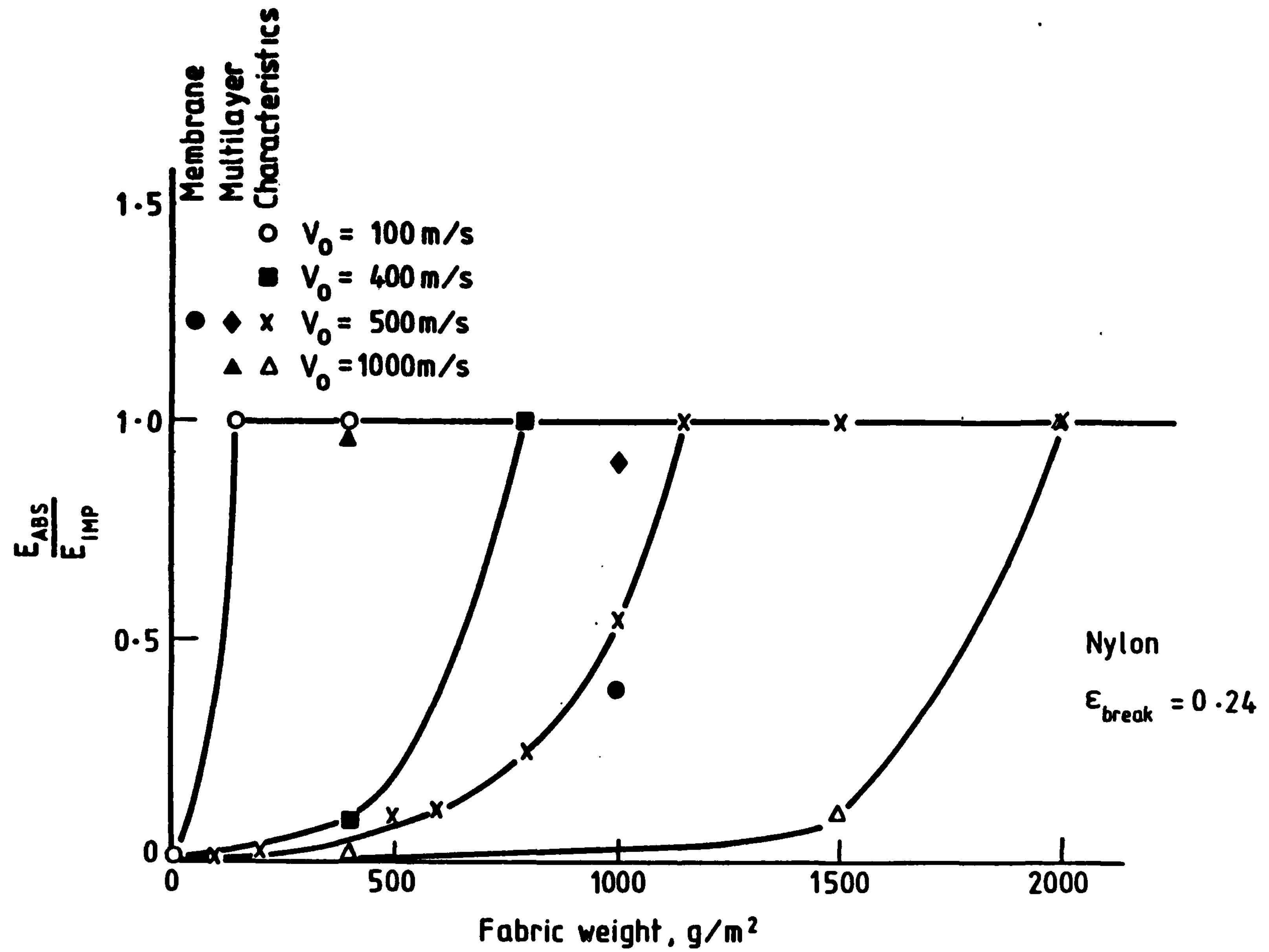

Kevlar
Break
Safe
Adeyefa, Fig. 5.34
$V_{50}$ (Experimental)
1000
500
0
$V_{50}$ m/s
0
1000
2000
3000
4000
Fabric weight, g/m$^{-2}$

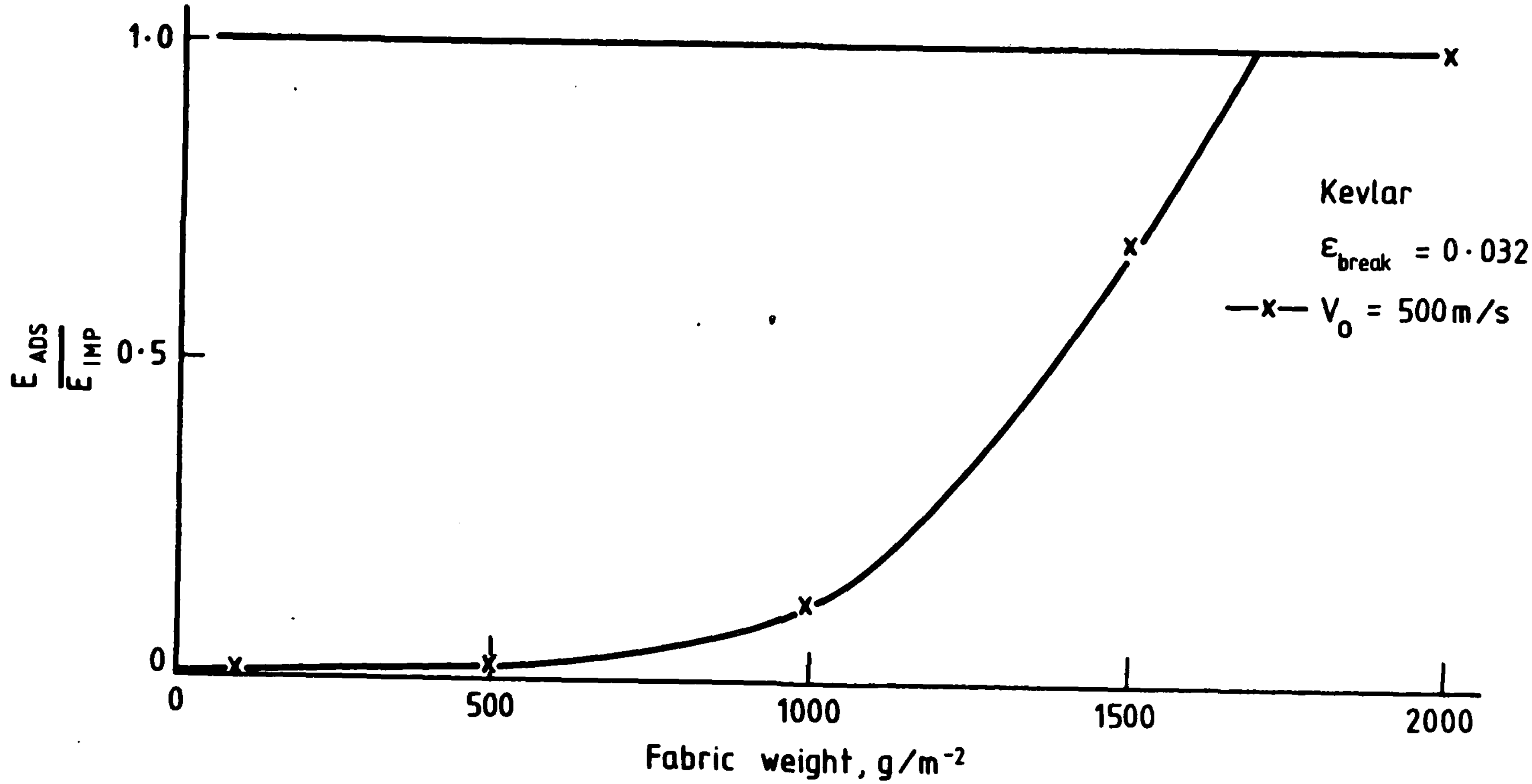
Fig. 1d

Figures 2a, to d show the energy absorbed plotted against area density for different impact velocities; when the projectile has stopped there is 100% energy absorption and thus at those points the graph is parallel to the fabric weight axis; the poor performance of Kevlar as predicted by the multilayer model is shown in Fig.2d by those points lying near the horizontal axis. These point do lie below the experimental fit and more data at lower velocities are now suggested. Fig.2c also shows the poor predicted performance as indicated by the multilayer model, in this case for nylon.




Energy v fabric weight

Fig. 2a




Energy v fabric weight

Fig.2b

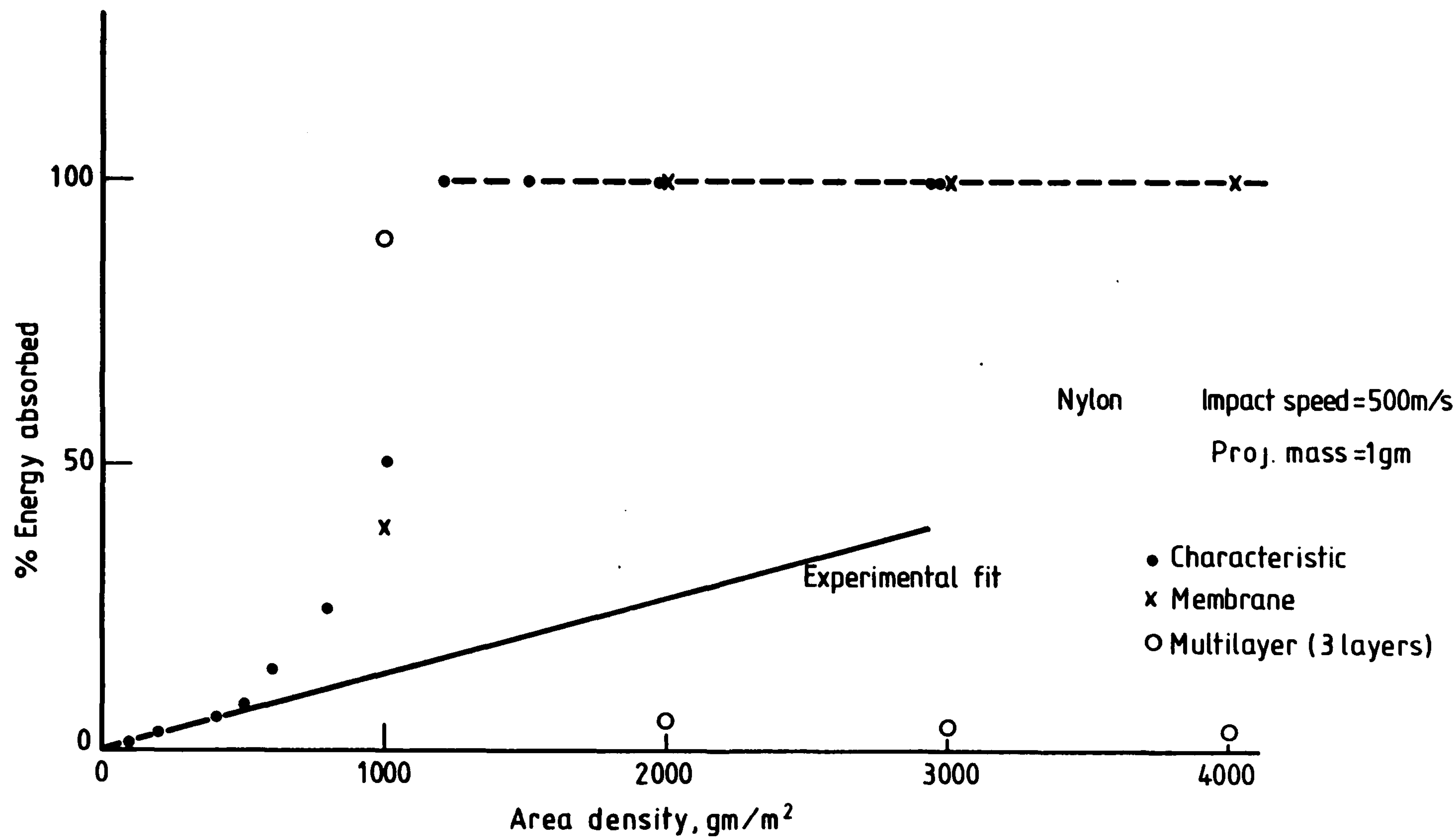
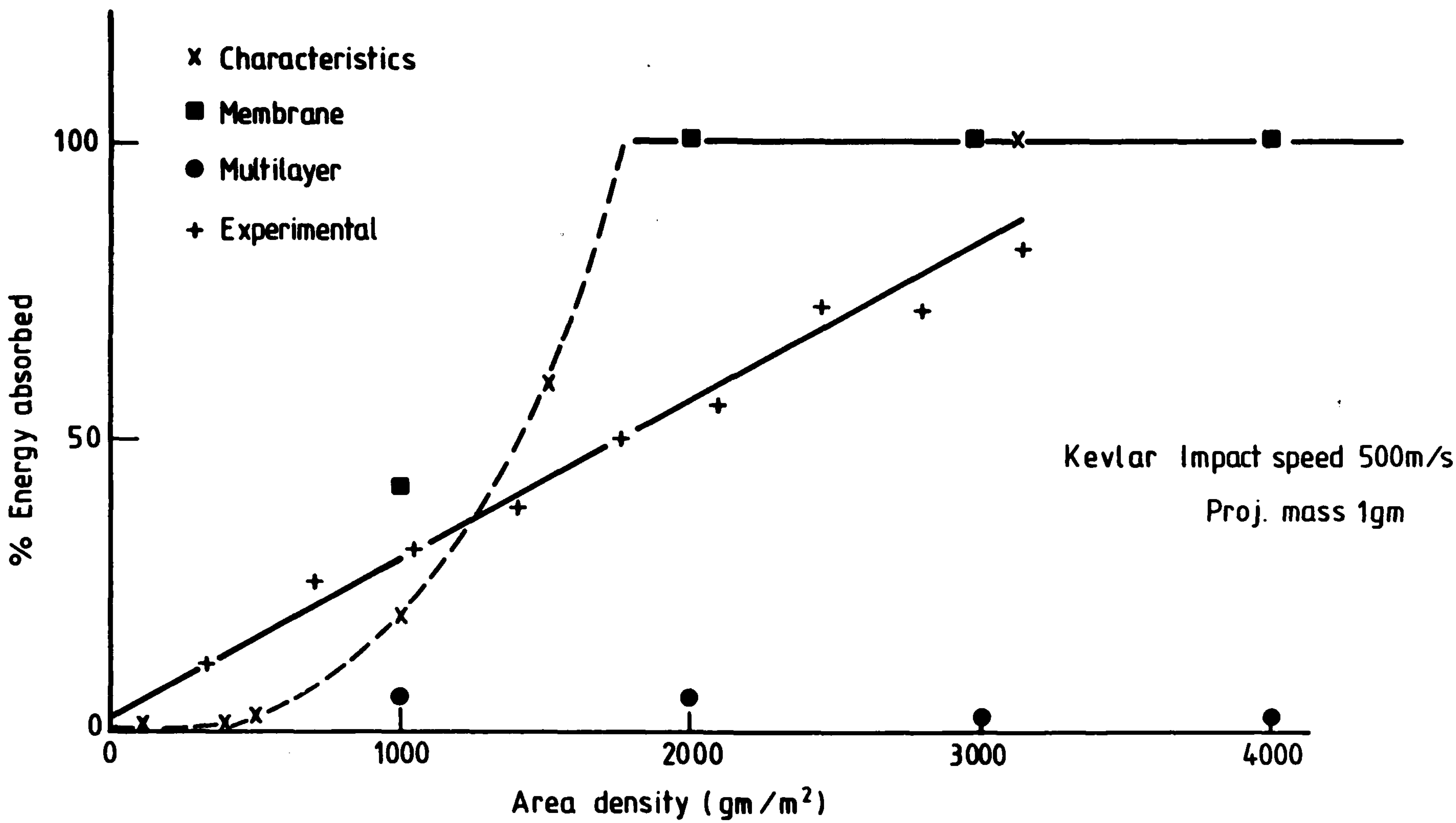

% Energy absorbed
100
50
0
1000
2000
3000
4000
Area density, gm/m²
Nylon
Impact speed=500m/s
Proj. mass=1gm
• Characteristic
x Membrane
O Multilayer (3 layers)
Experimental fit

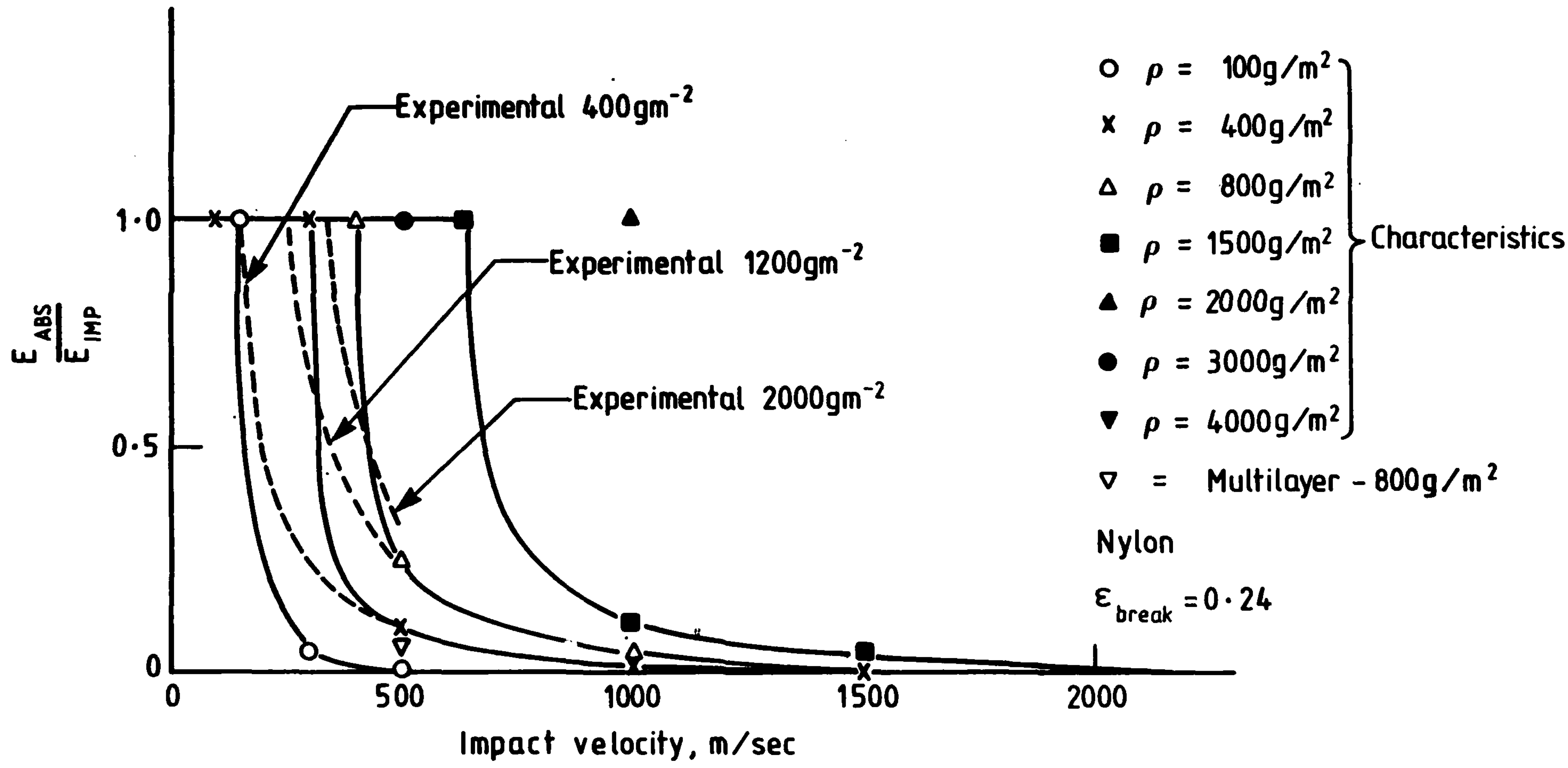
Fig. 2c



x Characteristics
■ Membrane
● Multilayer
+ Experimental
100
50
0
% Energy absorbed
0
1000
2000
3000
4000
Area density (gm/m²)
Kevlar Impact speed 500m/s
Proj. mass 1gm


Fig. 2d

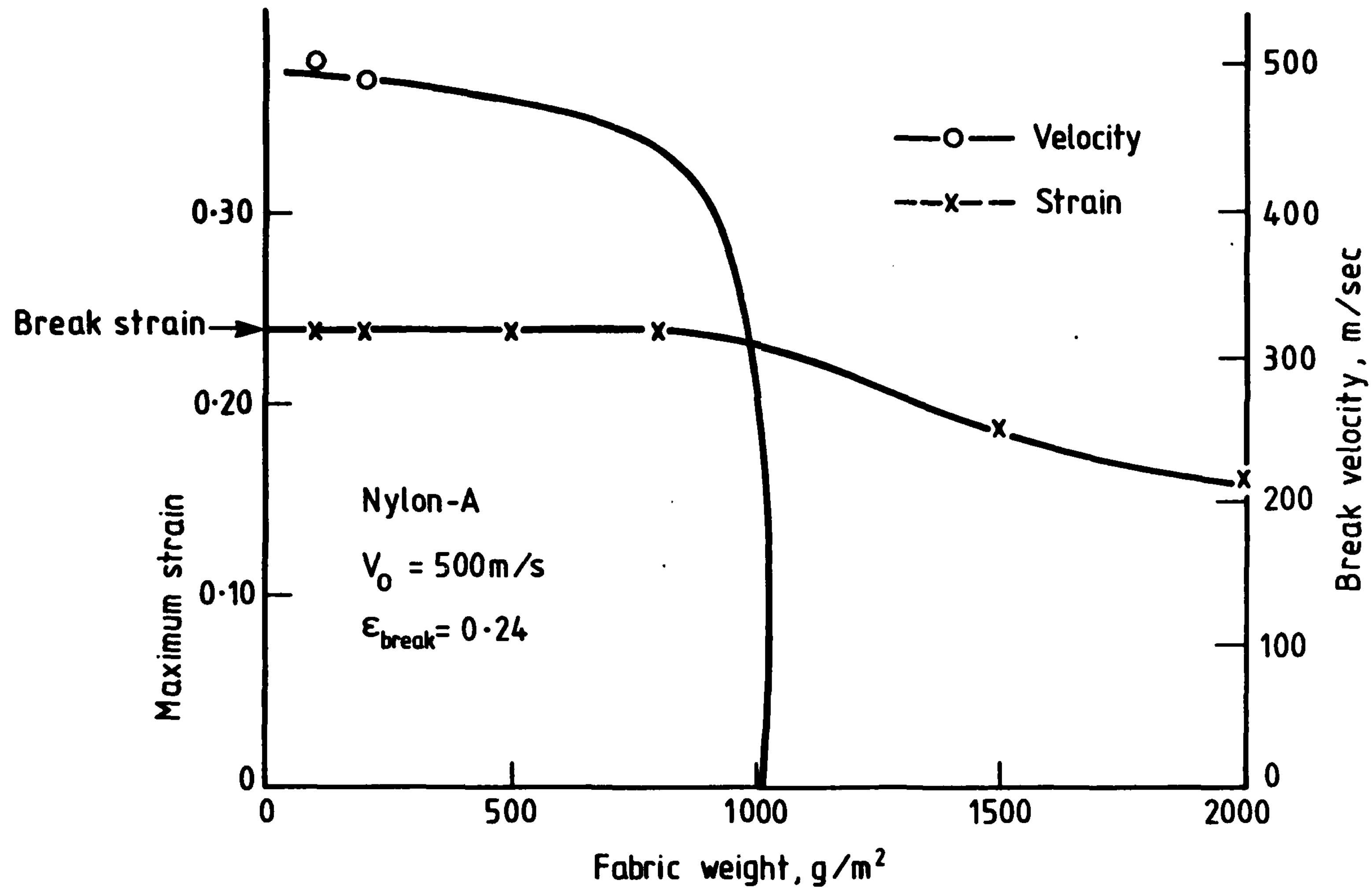
Figure 3a, shows the energies absorbed plotted against impact velocities for different material densities for nylon: Data does not presently exist for Kevlar. This together with figure 2a can yield the $V_{50}$ for each material since this is attained from the corner of the curve; obviously for low velocity the projectile is stopped and 100% energy is absorbed whereas at higher velocities the projectile passes through the fabric and emerges with lower velocity.




Energy v impact velocity

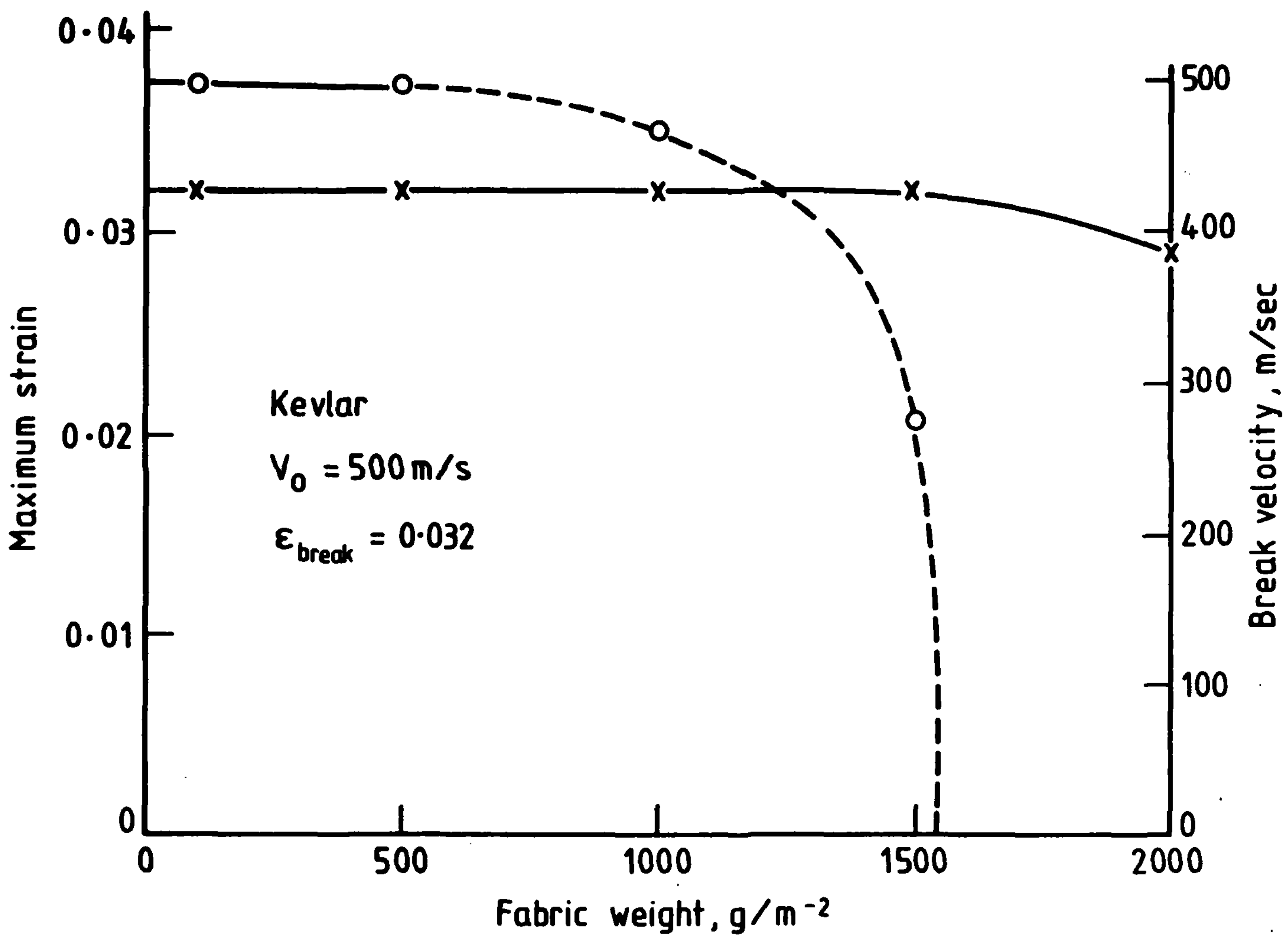
Fig. 3a

Figure 4a, b shows the variation of maximum strain and projectile velocities at break for an impact velocity of 500 m/s for different fabric weights; for small fabric weights the maximum strain is the breaking strain of nylon and Kevlar respectively and the velocity at break is close to the impact velocity. For heavy materials the velocity at break falls off but the strain at break must still be the breaking strain. For heavier materials which stop the projectile the maximum strain must be less than the breaking strain. In the first part of these curves (penetration) it is useful to look at the velocity at break whereas in the later part (stopping) it is sensible to look at the maximum strain. These results have been obtained from the characteristics model.




Maximum strain and break velocity vs fabric weight

Fig. 4a




Maximum strain and break velocity vs fabric weight

Fig.4b

Figures 5a-e show for an impact velocity of 500 m/s and different fabric weights (Nylon, 100, 500, 1000, 1500 and 2000 gm/m$^2$) the variation of projectile velocity, displacement and energy and fabric fibre strain and tension with time for nylon.

Figure 5f-j show again for nylon, area densities 400 gm/m$^2$, the same behaviour for different impact velocities (100, 300, 500, 1000 and 2000 m/s.)

Fig. 5k-o; shows for Kevlar the same information for an impact velocity 500 m/s and for different fabric weights (100, 500, 1000, 1500 and 2000 gm/m$^2$).

Fig. 5 p-s; again for Kevlar shows the effect of different impact speed (500, 1000, 1500 and 2000) on fabric weight 400 gm/m$^2$.

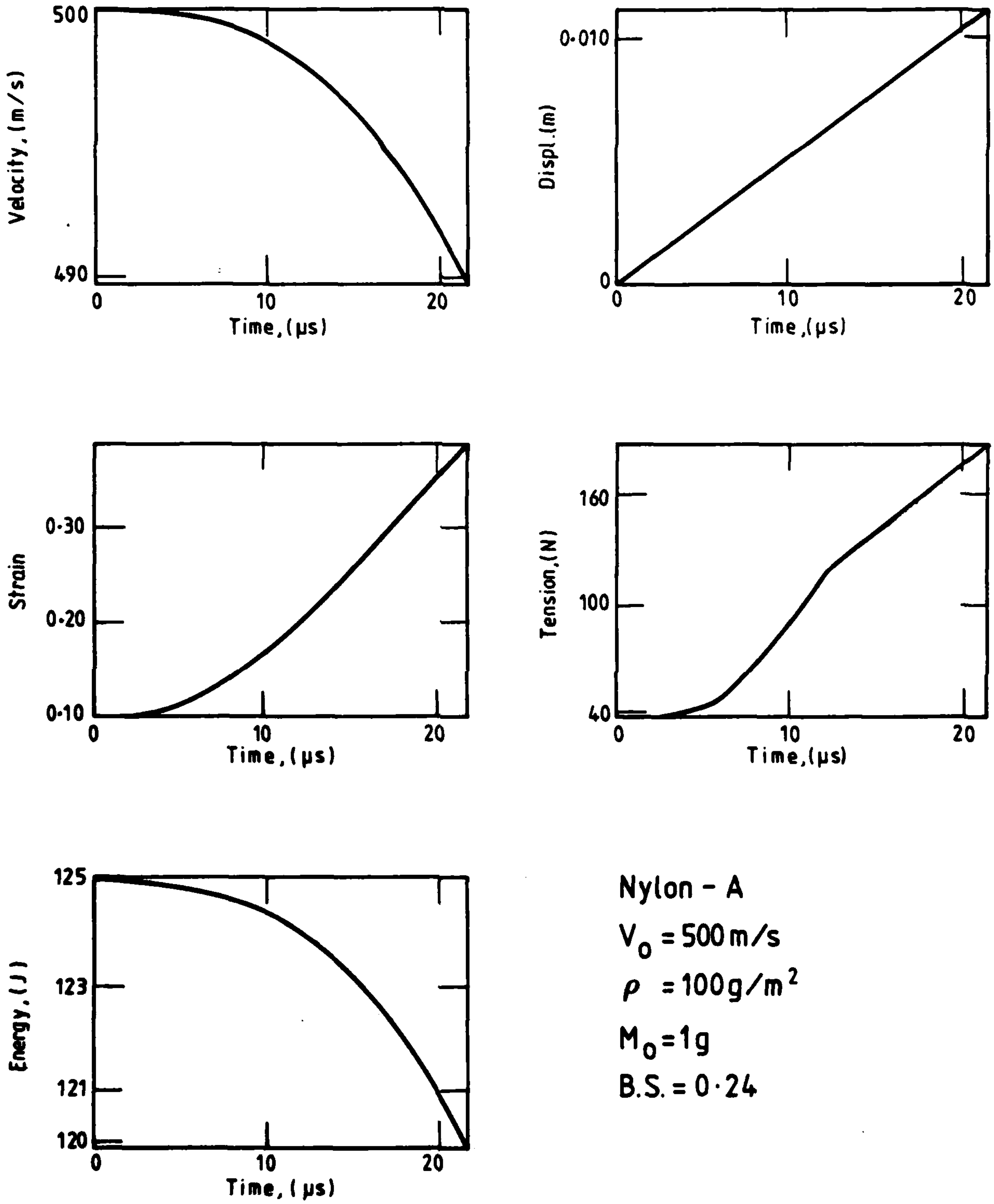
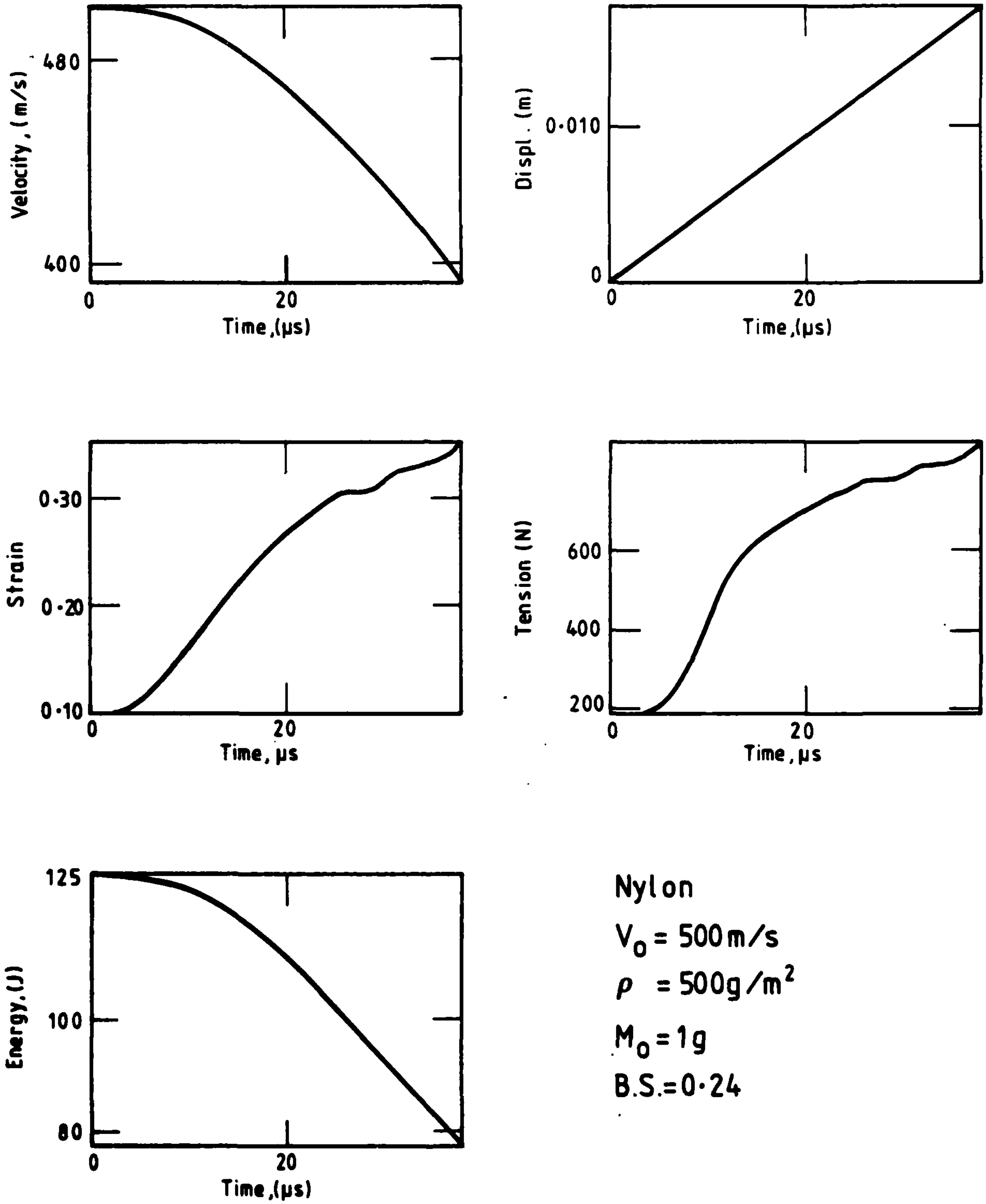
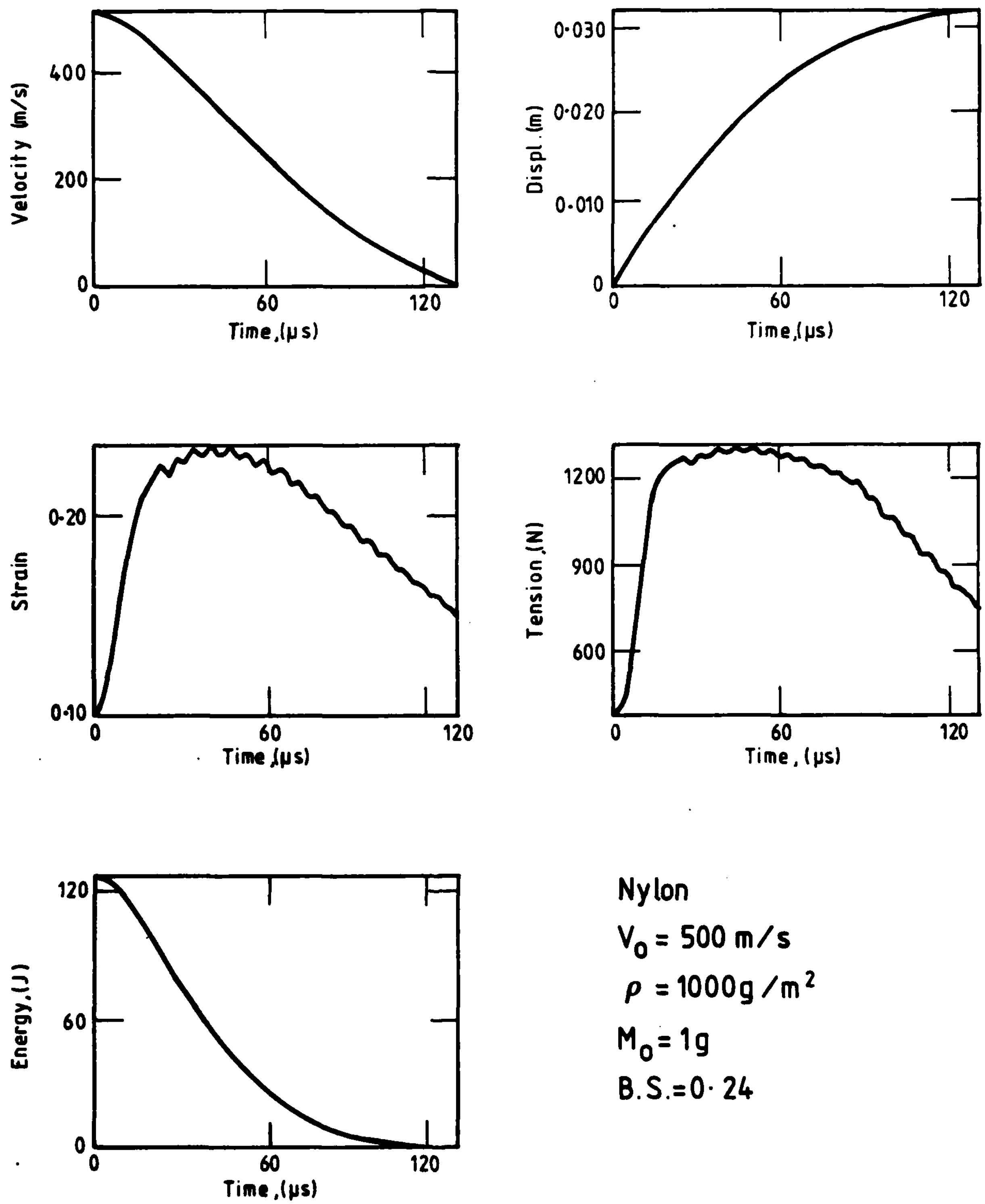

500
490
Velocity, (m/s)
0
10
20
Time, (μs)
0·010
0
Displ.(m)
Time ,(μs)
0·30
0·20
0·10
Strain
Time, (μs)
160
100
40
Tension,(N)
Time,(μs)
125
123
121
120
Energy, (J)
Time, (μs)
Nylon - A
$V_o = 500\,m/s$
$\rho = 100\,g/m^2$
$M_o = 1\,g$
B.S. = 0·24

Fig.5 (a-e)

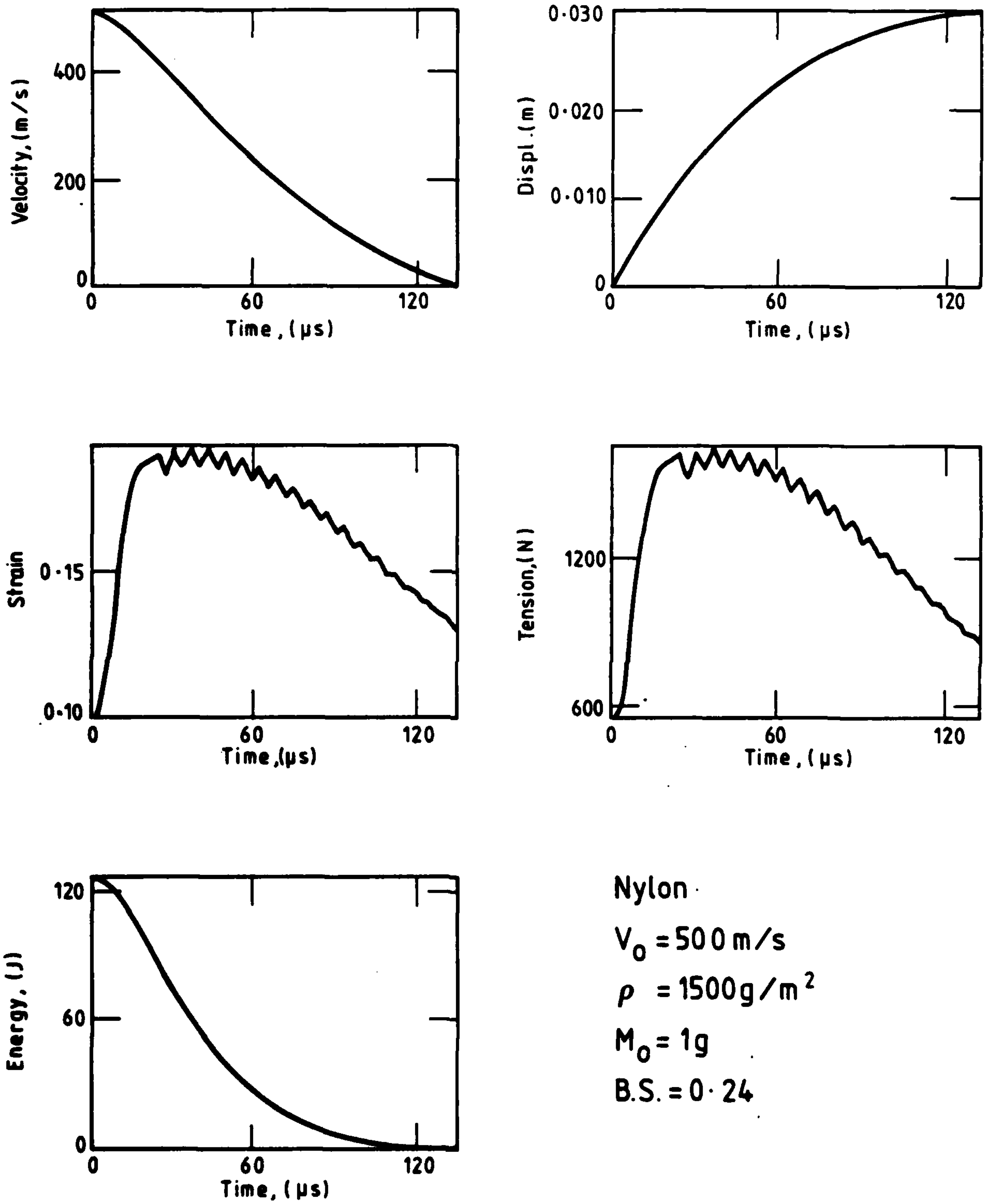


Velocity, (m/s)
480
400
0
20
Time,(μs)
Displ. (m)
0·010
0
0
20
Time,(μs)
Strain
0·30
0·20
0·10
0
20
Time, μs
Tension (N)
600
400
200
0
20
Time, μs
Energy,(J)
125
100
80
0
20
Time,(μs)
Nylon
V0 = 500 m/s
ρ = 500g/m2
M0 = 1g
B.S.= 0·24

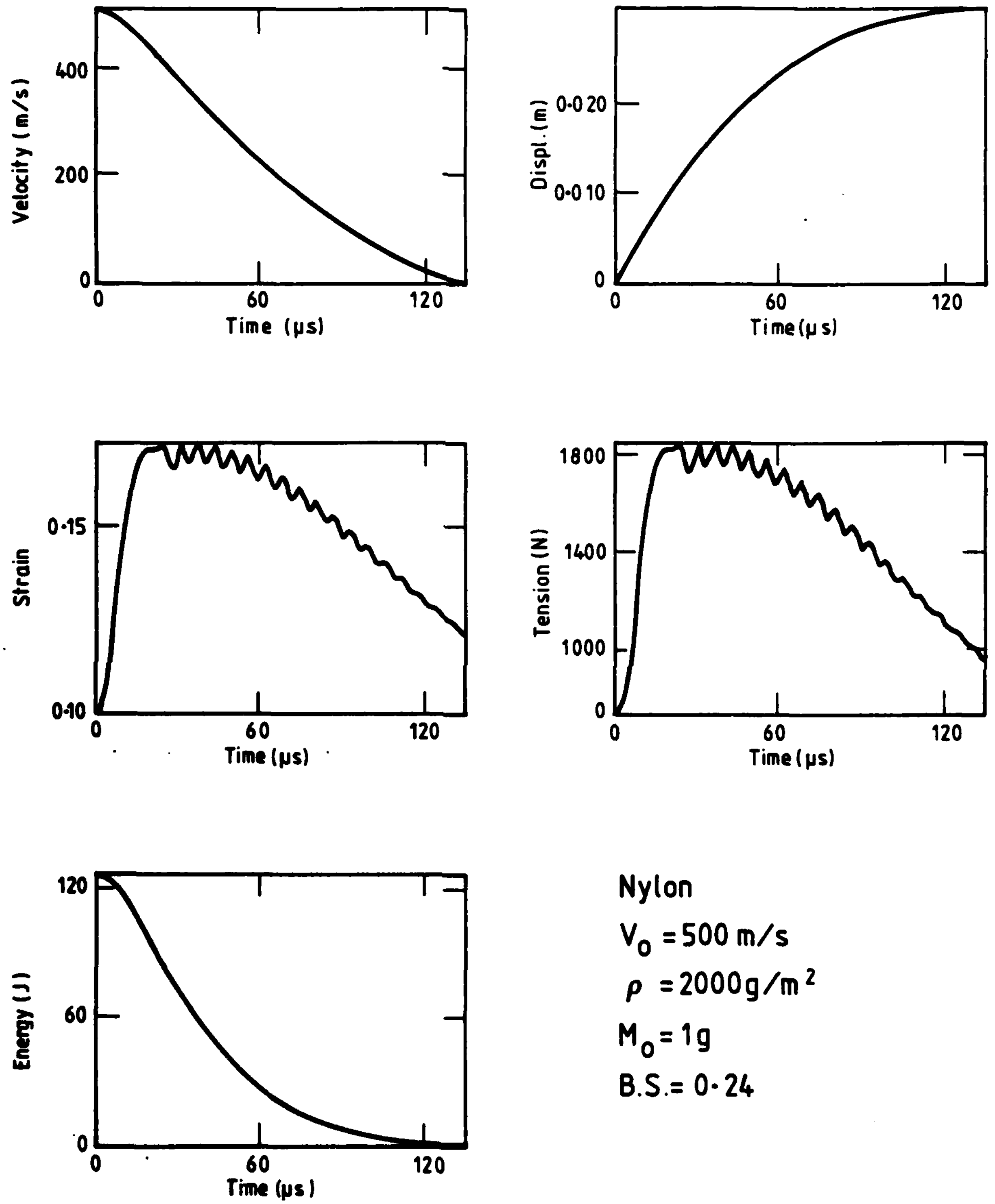

(b)


Velocity (m/s)
400
200
0
Time,(μs)
0
60
120
Displ. (m)
0·030
0·020
0·010
0
Time,(μs)
Strain
0·20
0·10
Time,(μs)
Tension,(N)
1200
900
600
Time, (μs)
Energy,(J)
120
60
0
Time,(μs)
Nylon
$V_0$ = 500 m/s
$\rho$ = 1000g/$m^2$
$M_0$ = 1g
B.S.=0· 24

(c)


Velocity, (m/s)
400
200
0
0
60
120
Time, (μs)
Displ. (m)
0·030
0·020
0·010
0
0
60
120
Time, (μs)
Strain
0·15
0·10
0
60
120
Time, (μs)
Tension, (N)
1200
600
0
60
120
Time, (μs)
Energy, (J)
120
60
0
0
60
120
Time, (μs)
Nylon
$V_0 = 500$ m/s
$\rho = 1500 g/m^2$
$M_0 = 1g$
B.S. = 0·24

(d)


Velocity (m/s)
400
200
0
0
60
120
Time (μs)
Displ. (m)
0·020
0·010
0
0
60
120
Time (μs)
Strain
0·15
0·10
0
60
120
Time (μs)
Tension (N)
1800
1400
1000
0
0
60
120
Time (μs)
Energy (J)
120
60
0
0
60
120
Time (μs)
Nylon
V0 = 500 m/s
ρ = 2000g/m2
M0 = 1g
B.S. = 0·24

(e)

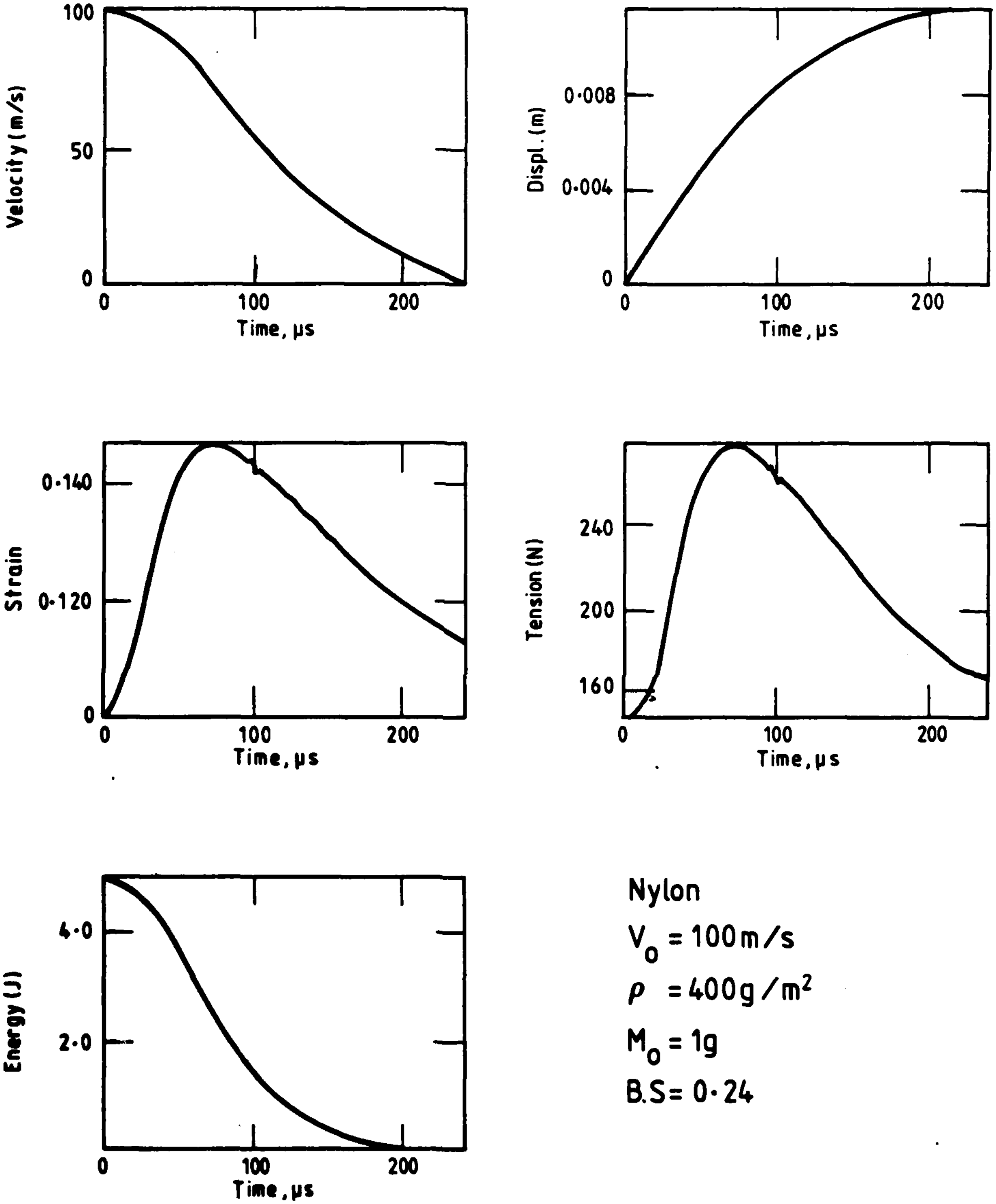
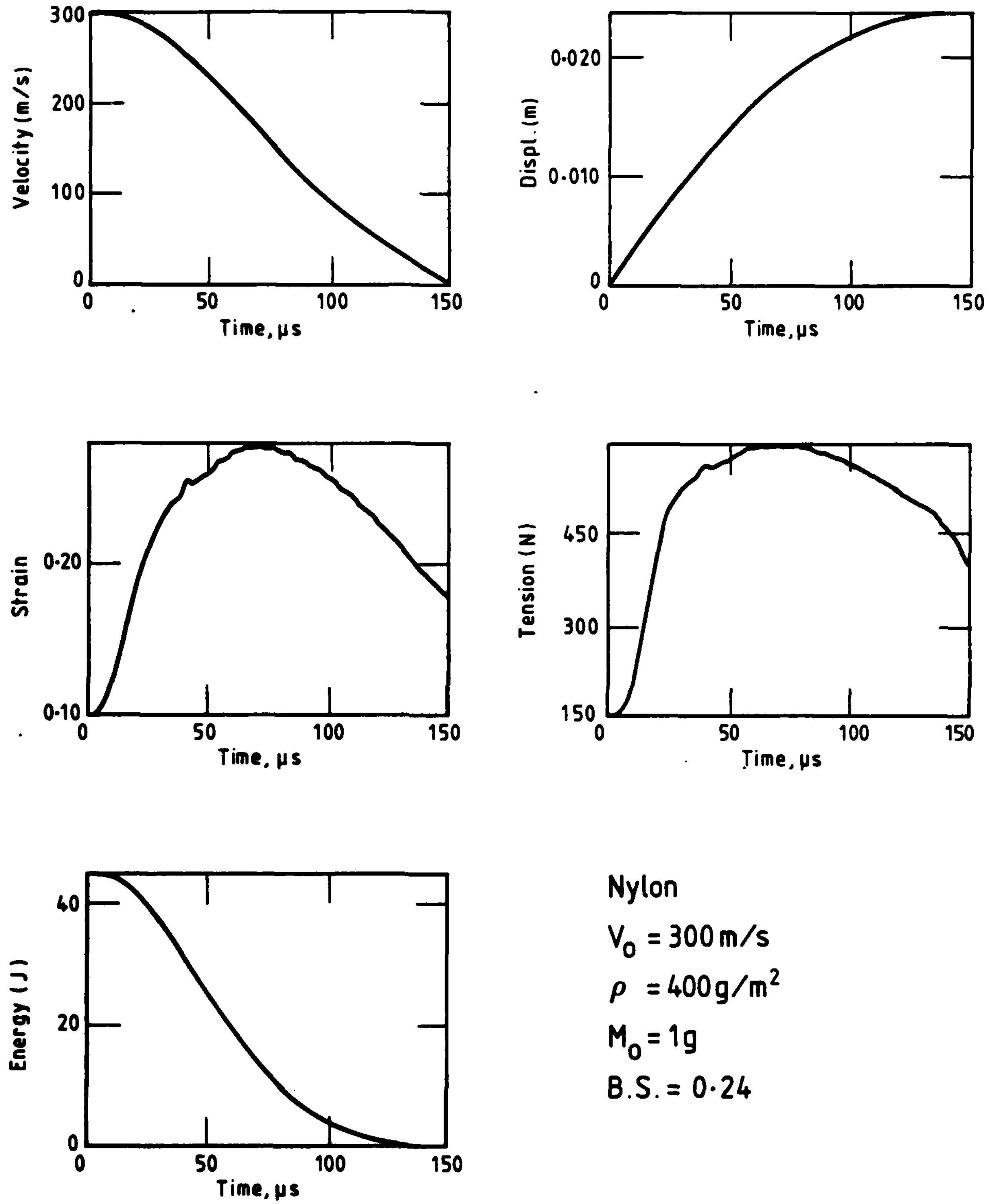
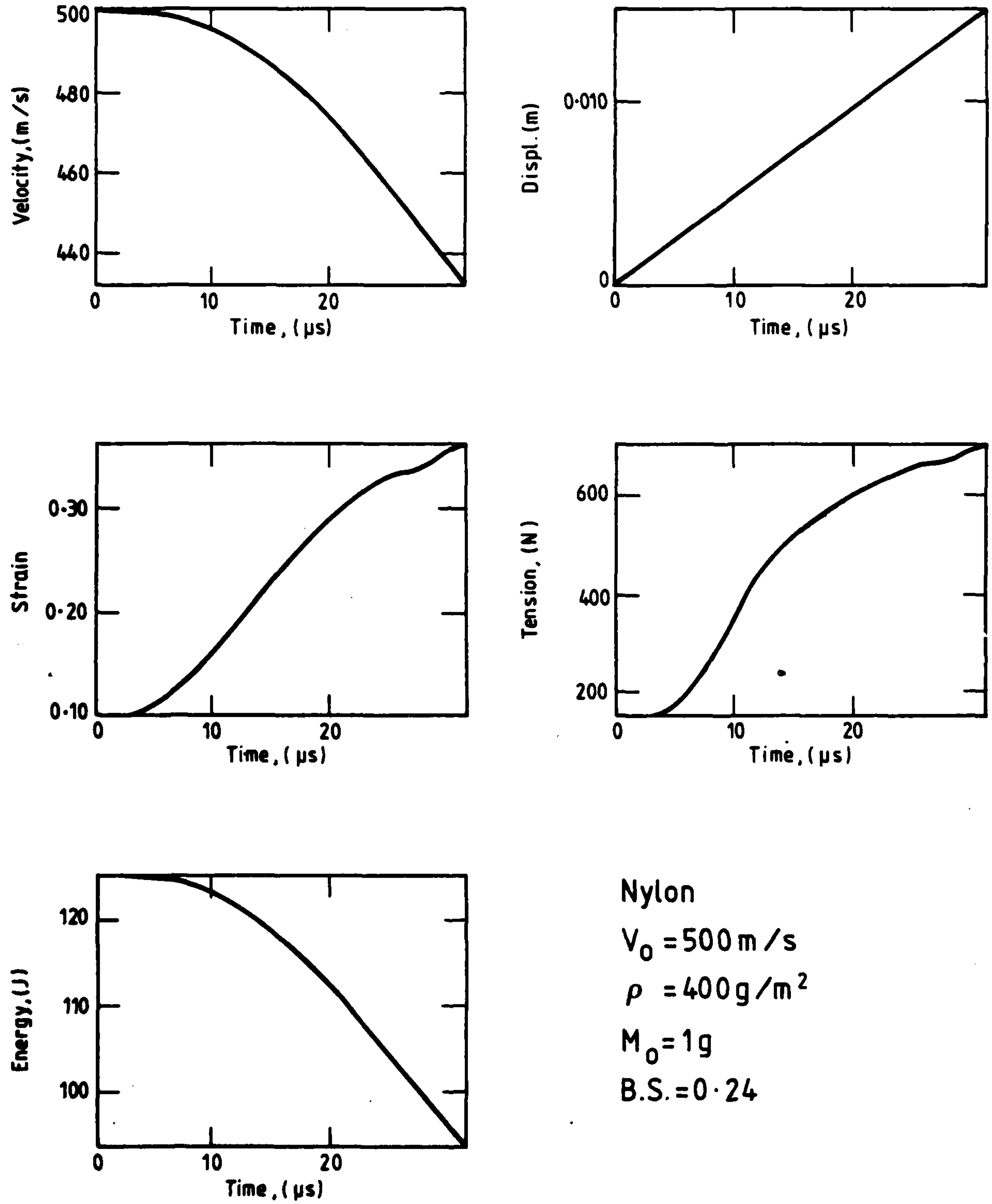

Velocity (m/s)
Time, μs
Displ. (m)
Time, μs
Strain
Time, μs
Tension (N)
Time, μs
Energy (J)
Time, μs
Nylon
$V_o = 100 m/s$
$\rho = 400 g/m^2$
$M_o = 1 g$
B.S = 0·24

Fig.5(f-j)

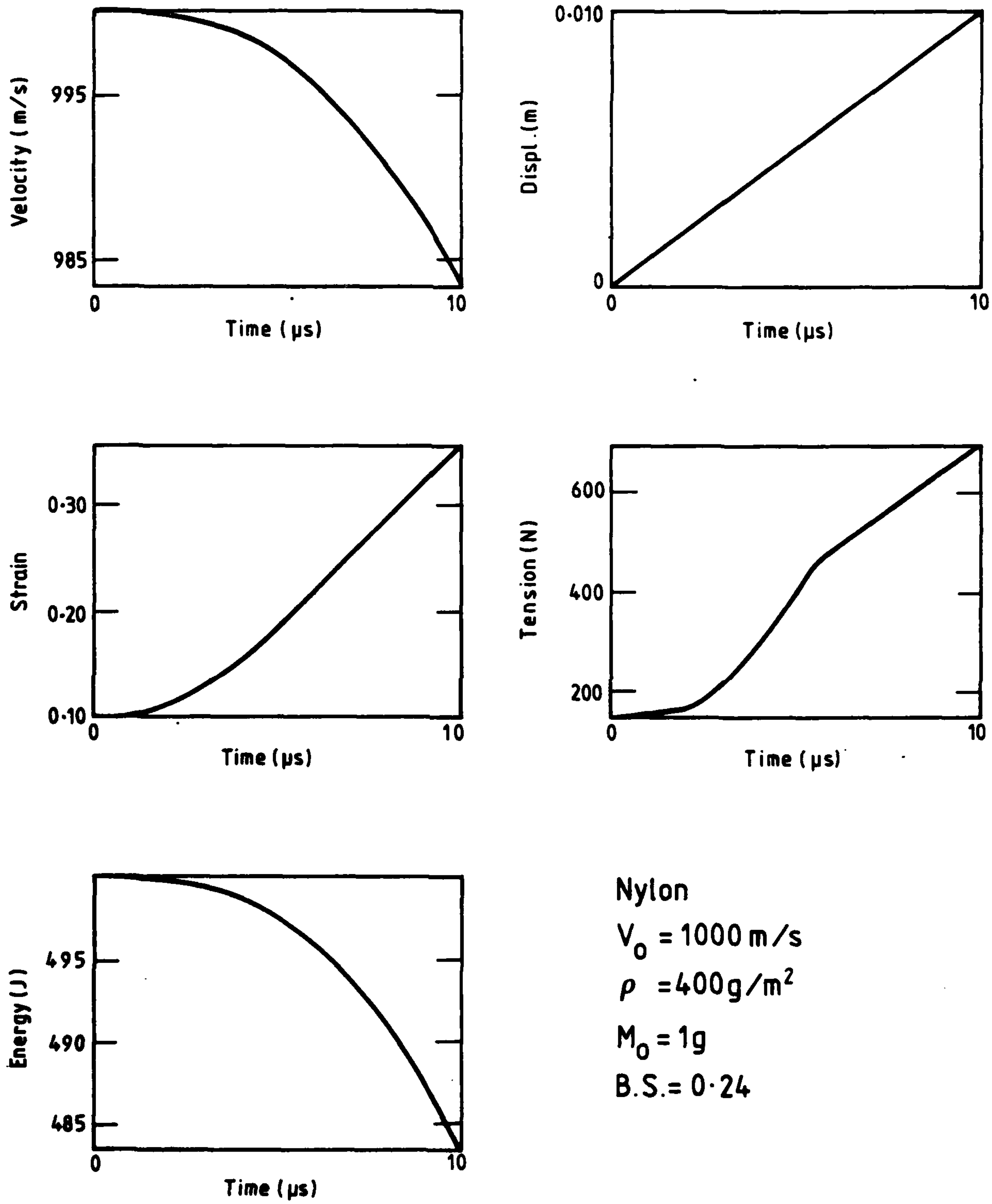


Velocity (m/s)
300
200
100
0
0
50
100
150
Time, μs
Displ. (m)
0·020
0·010
0
0
50
100
150
Time, μs
Strain
0·20
0·10
0
50
100
150
Time, μs
Tension (N)
450
300
150
0
50
100
150
Time, μs
Energy (J)
40
20
0
0
50
100
150
Time, μs
Nylon
$V_o$ = 300 m/s
$\rho$ = 400 g/m$^2$
$M_o$ = 1g
B.S. = 0·24


(g)


500
480
460
440
Velocity, (m/s)
0
10
20
Time, (μs)
0·010
0
Displ. (m)
Time, (μs)
0·30
0·20
0·10
Strain
Time, (μs)
600
400
200
Tension, (N)
Time, (μs)
120
110
100
Energy, (J)
Time, (μs)
Nylon
$V_0$ = 500 m/s
ρ = 400 g/m$^2$
$M_0$ = 1 g
B.S. = 0·24

(h)




Nylon

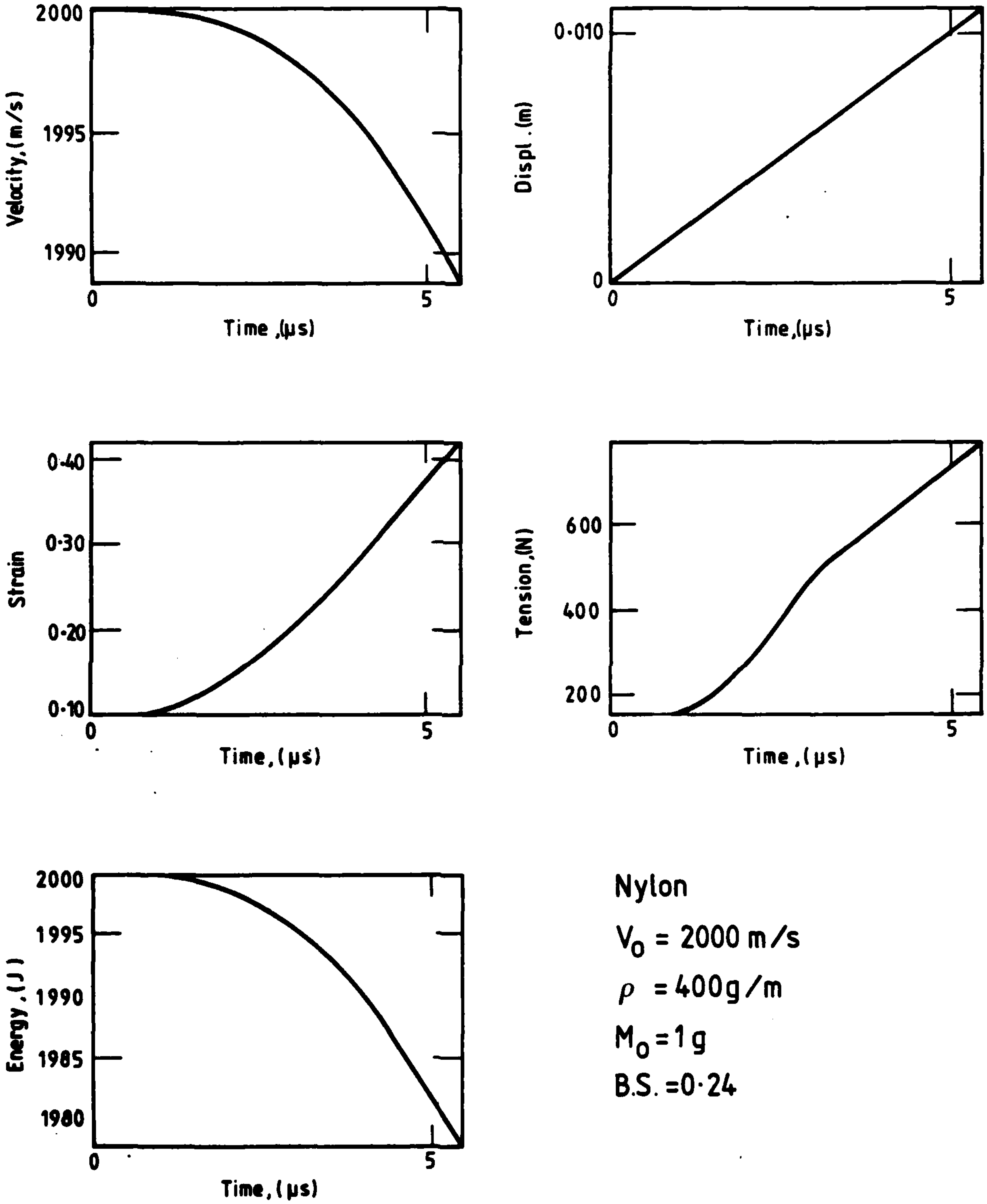
$V_0 = 1000\ m/s$

$\rho = 400 g/m^2$

$M_0 = 1g$

B.S.= 0·24

(i)



Velocity, (m/s)
2000
1995
1990
0
5
Time, (µs)
Displ. (m)
0·010
0
0
5
Time, (µs)
Strain
0·40
0·30
0·20
0·10
0
5
Time, (µs)
Tension, (N)
600
400
200
0
5
Time, (µs)
Energy, (J)
2000
1995
1990
1985
1980
0
5
Time, (µs)
Nylon
$V_0$ = 2000 m/s
$\rho$ = 400g/m
$M_0$ = 1 g
B.S. = 0·24


(j)

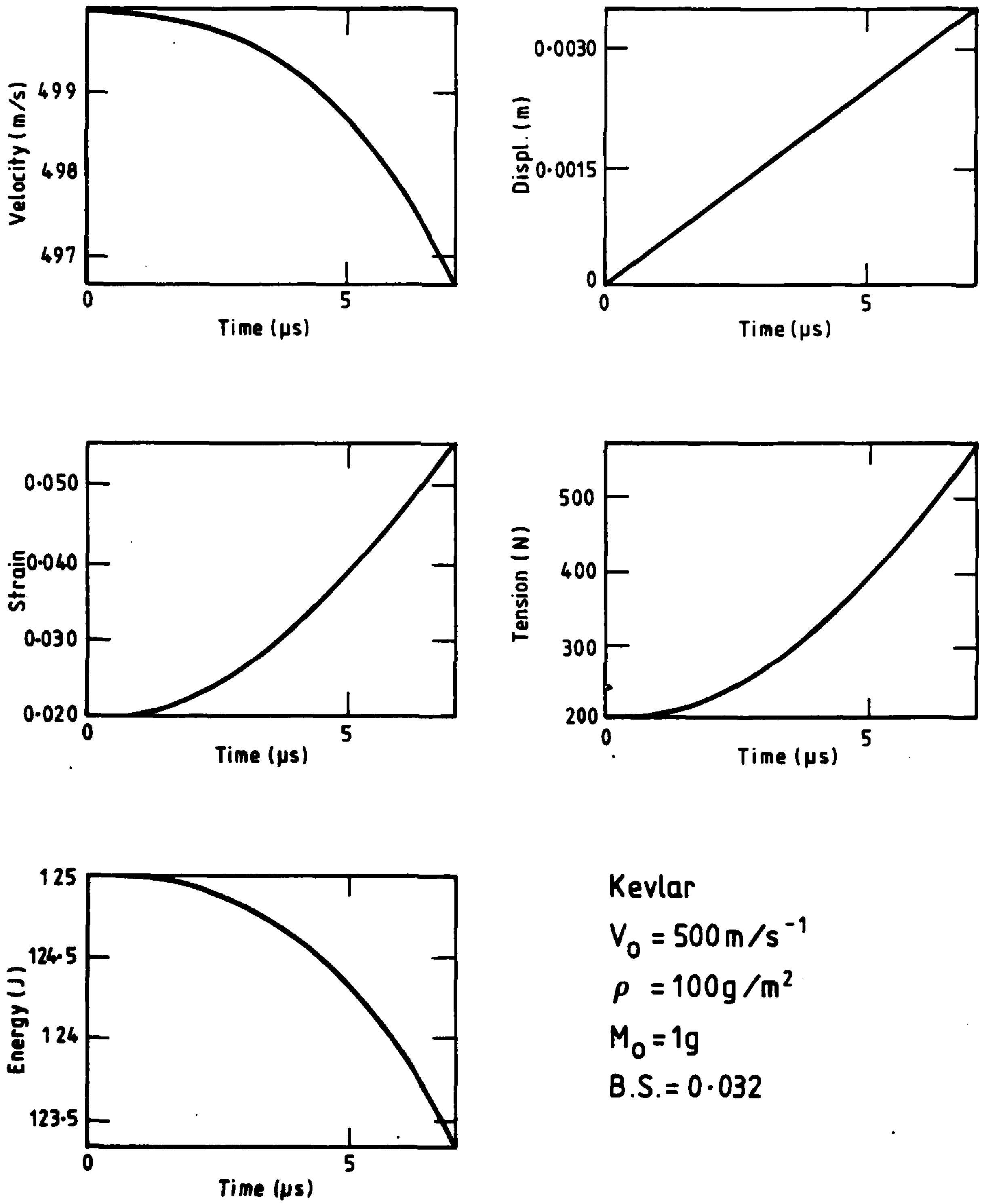
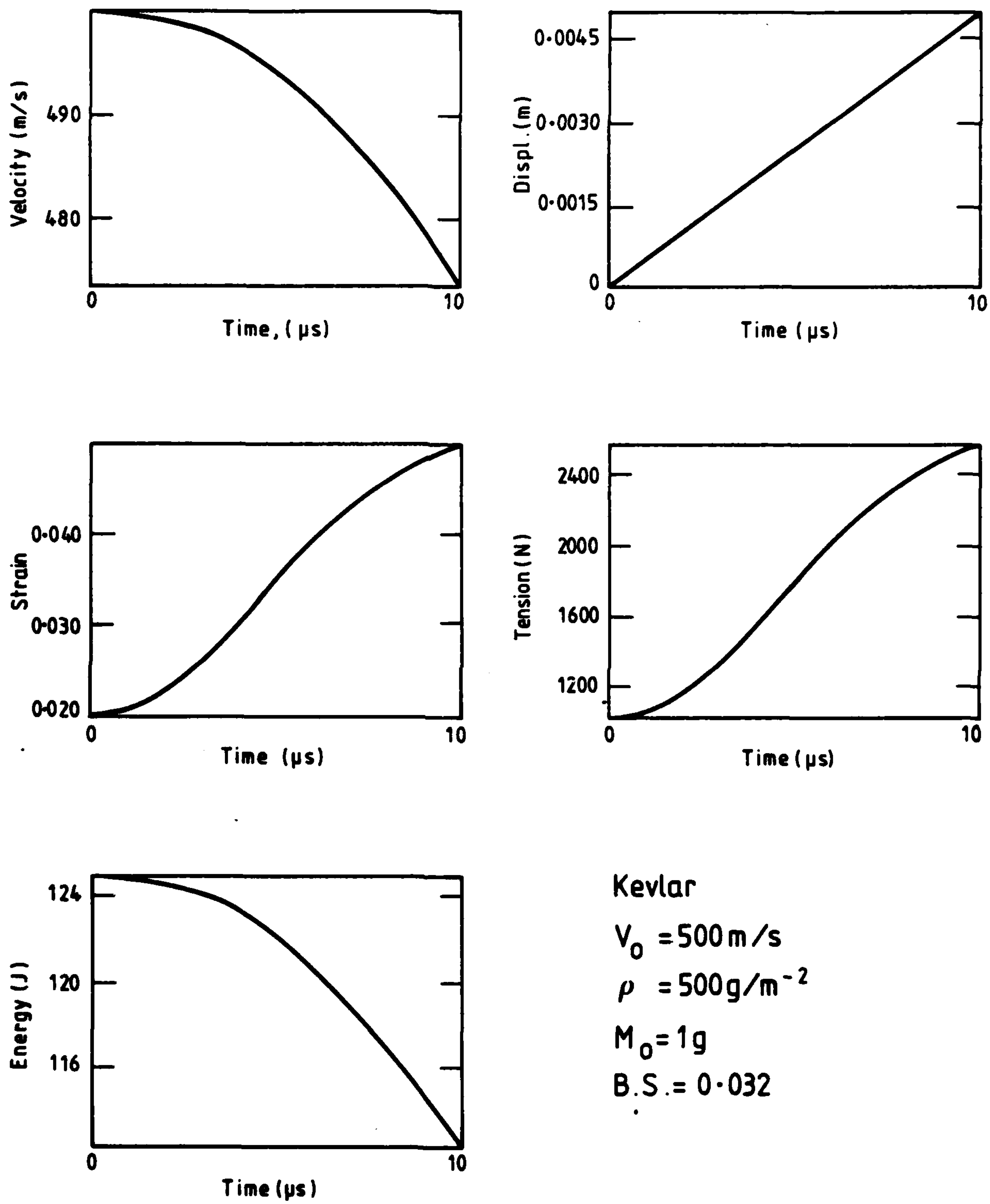
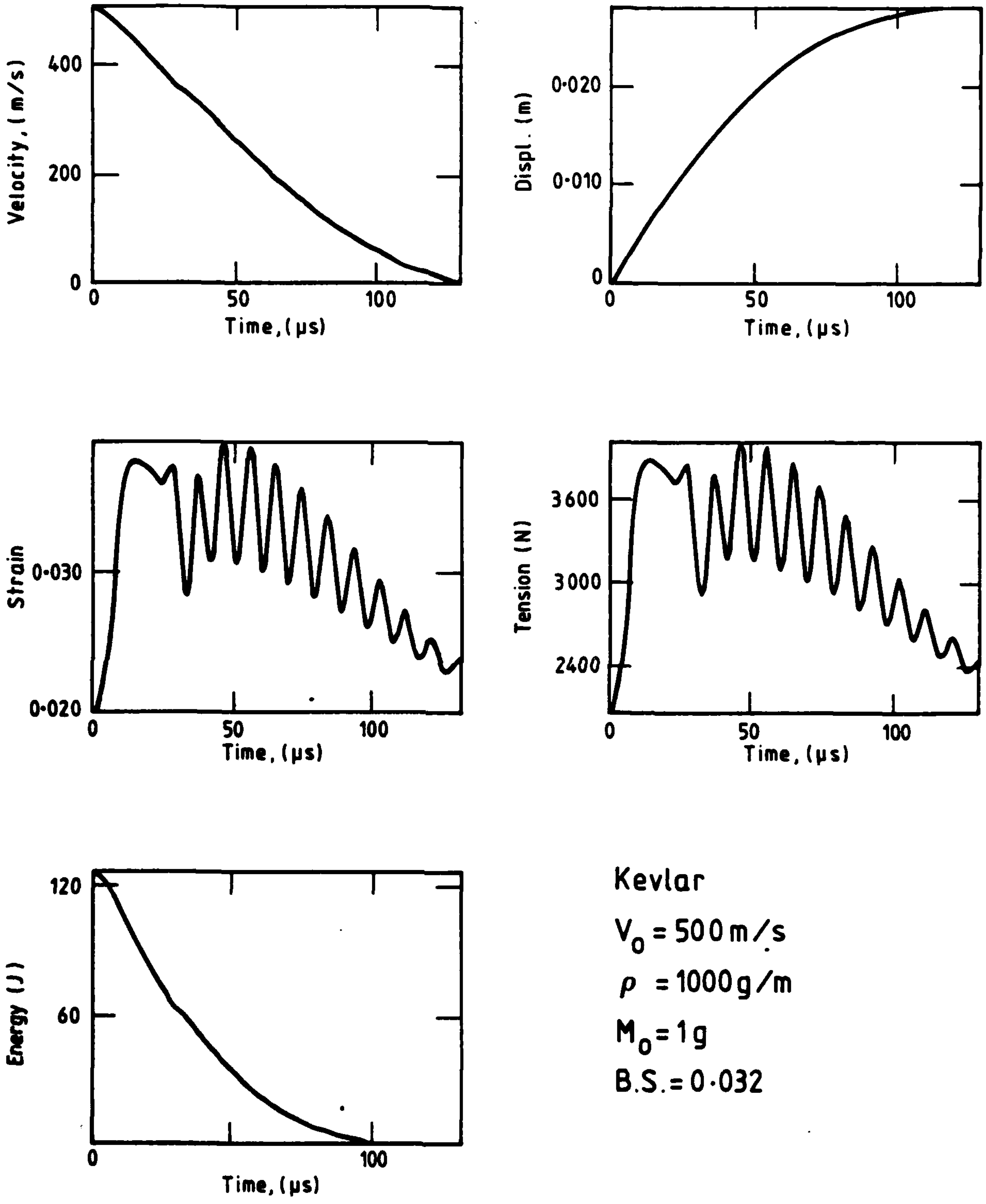

Velocity (m/s)
499
498
497
0
5
Time (μs)
Displ. (m)
0·0030
0·0015
0
0
5
Time (μs)
Strain
0·050
0·040
0·030
0·020
0
5
Time (μs)
Tension (N)
500
400
300
200
0
5
Time (μs)
Energy (J)
125
124·5
124
123·5
0
5
Time (μs)
Kevlar
V0 = 500m/s-1
ρ = 100g/m2
M0 = 1g
B.S. = 0·032

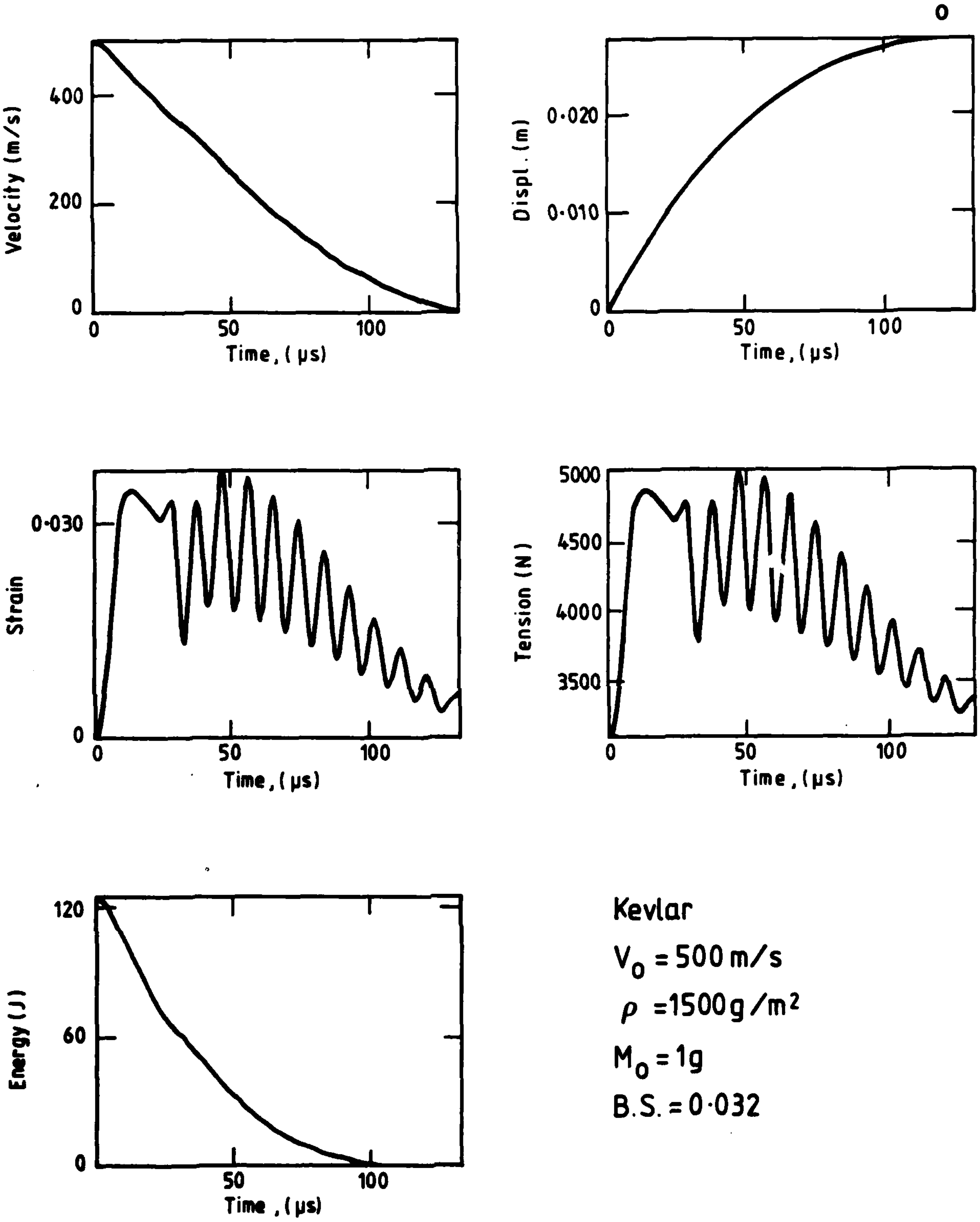
Fig. 5 (k-o)


Velocity (m/s)
490
480
0
10
Time, (μs)
Displ. (m)
0·0045
0·0030
0·0015
0
0
10
Time (μs)
Strain
0·040
0·030
0·020
0
10
Time (μs)
Tension (N)
2400
2000
1600
1200
0
10
Time (μs)
Energy (J)
124
120
116
0
10
Time (μs)
Kevlar
$V_o$ = 500 m/s
$\rho$ = 500 g/m$^{-2}$
$M_o$ = 1 g
B.S. = 0·032

(i)


Velocity, (m/s)
400
200
0
Time, (μs)
0
50
100
Displ. (m)
0·020
0·010
0
Time, (μs)
Strain
0·030
0·020
Time, (μs)
Tension (N)
3600
3000
2400
Time, (μs)
Energy (J)
120
60
Time, (μs)
Kevlar
$V_0 = 500$ m/s
$\rho = 1000$ g/m
$M_0 = 1$ g
B.S. = 0·032

(m)




Kevlar

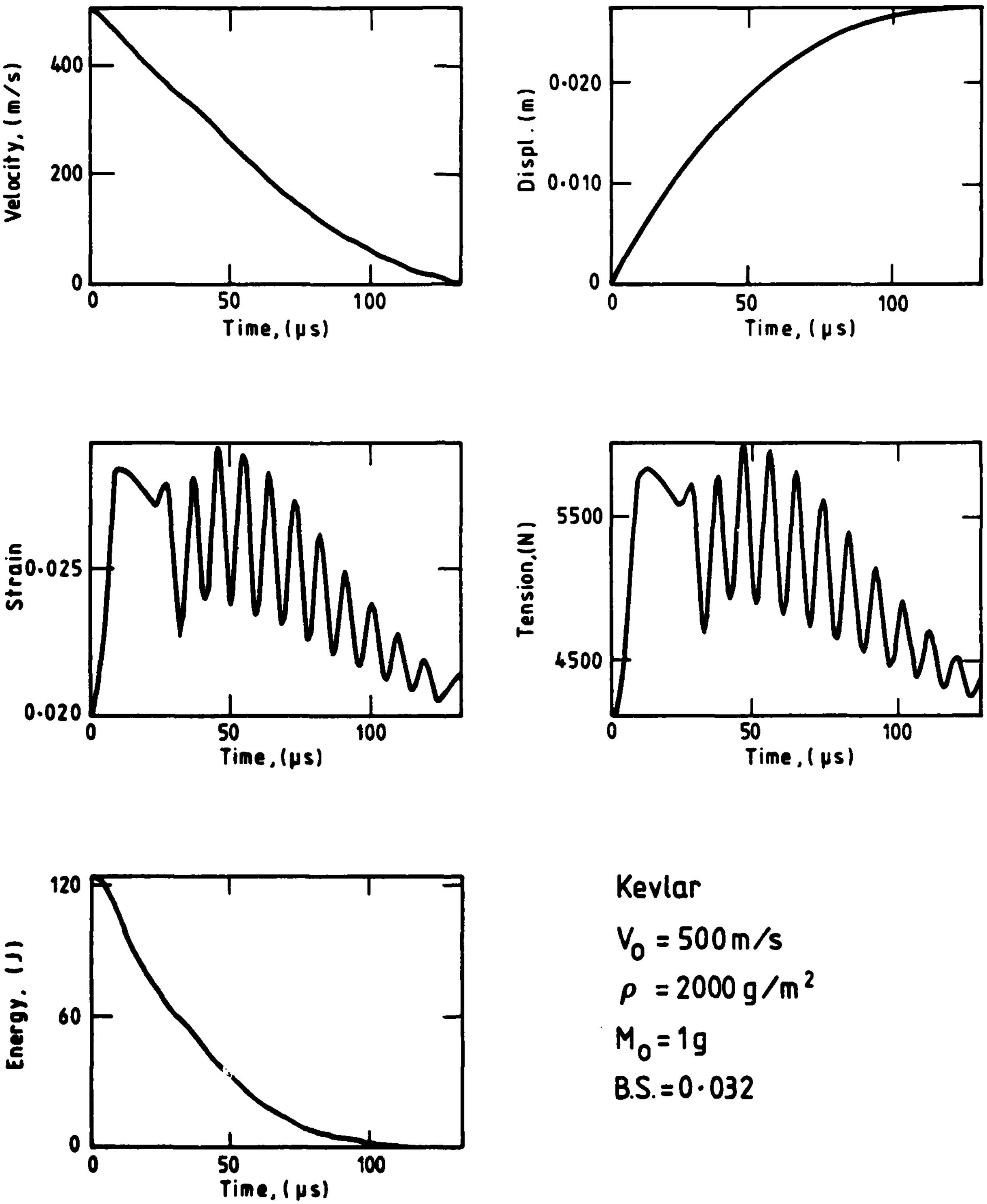
$V_0 = 500\,m/s$

$\rho = 1500\,g/m^2$

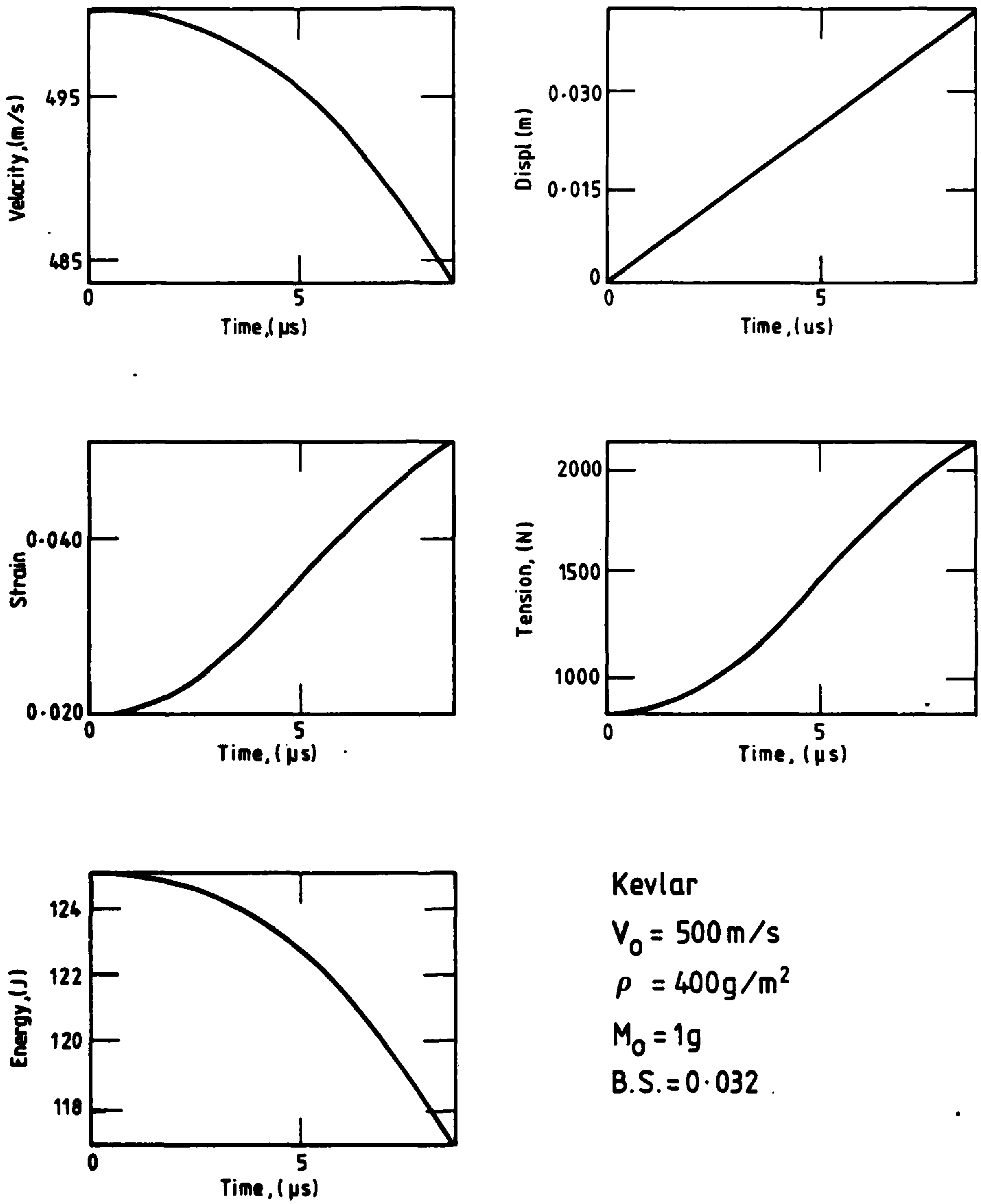
$M_0 = 1g$

B.S. = 0·032

(n)

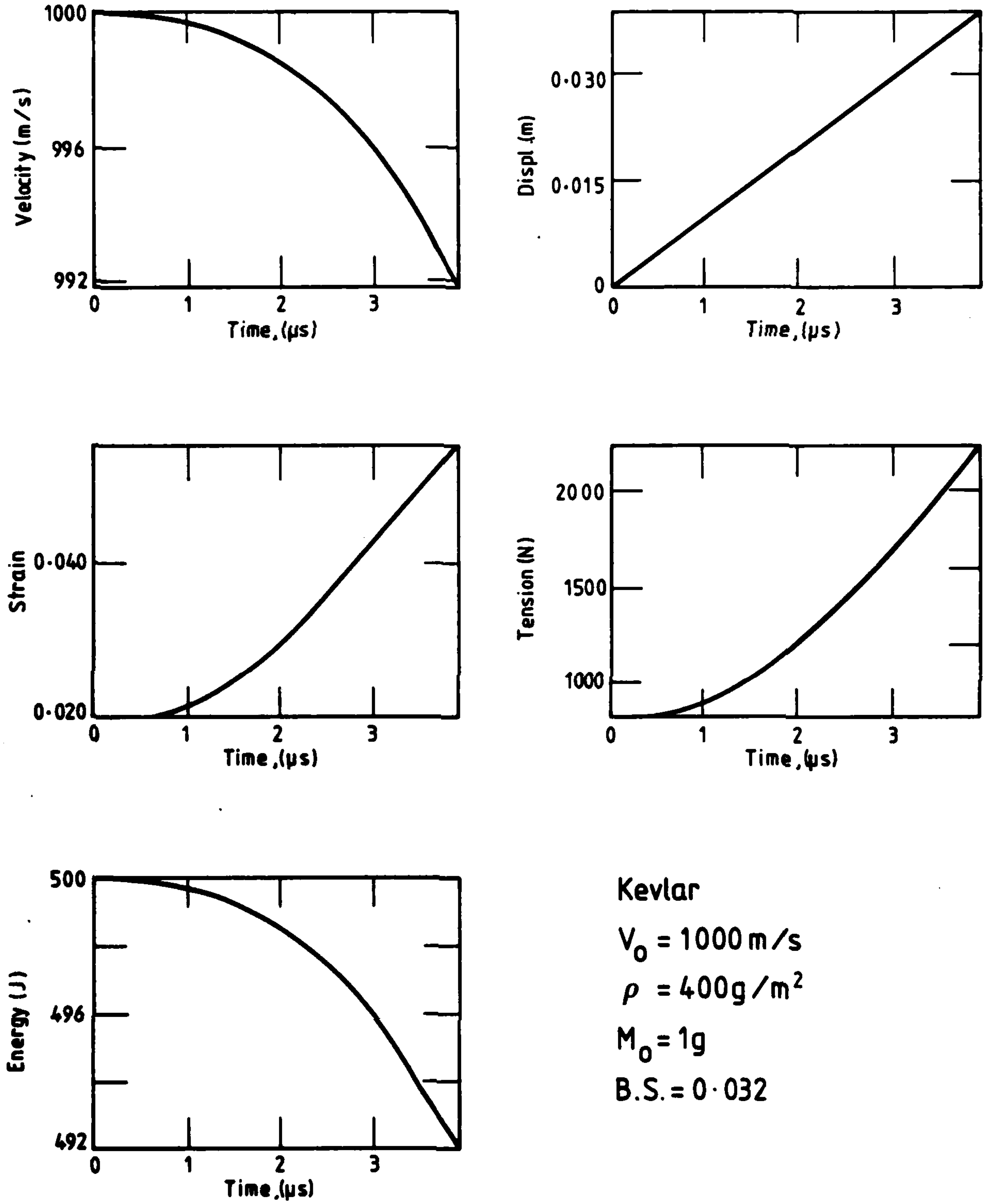

Velocity, (m/s)
400
200
0
0
50
100
Time, (μs)
Displ. (m)
0·020
0·010
0
0
50
100
Time, (μs)
Strain
0·025
0·020
0
50
100
Time, (μs)
Tension, (N)
5500
4500
0
50
100
Time, (μs)
Energy, (J)
120
60
0
0
50
100
Time, (μs)
Kevlar
$V_0$ = 500 m/s
$\rho$ = 2000 g/m$^2$
$M_0$ = 1g
B.S. = 0·032

(o)

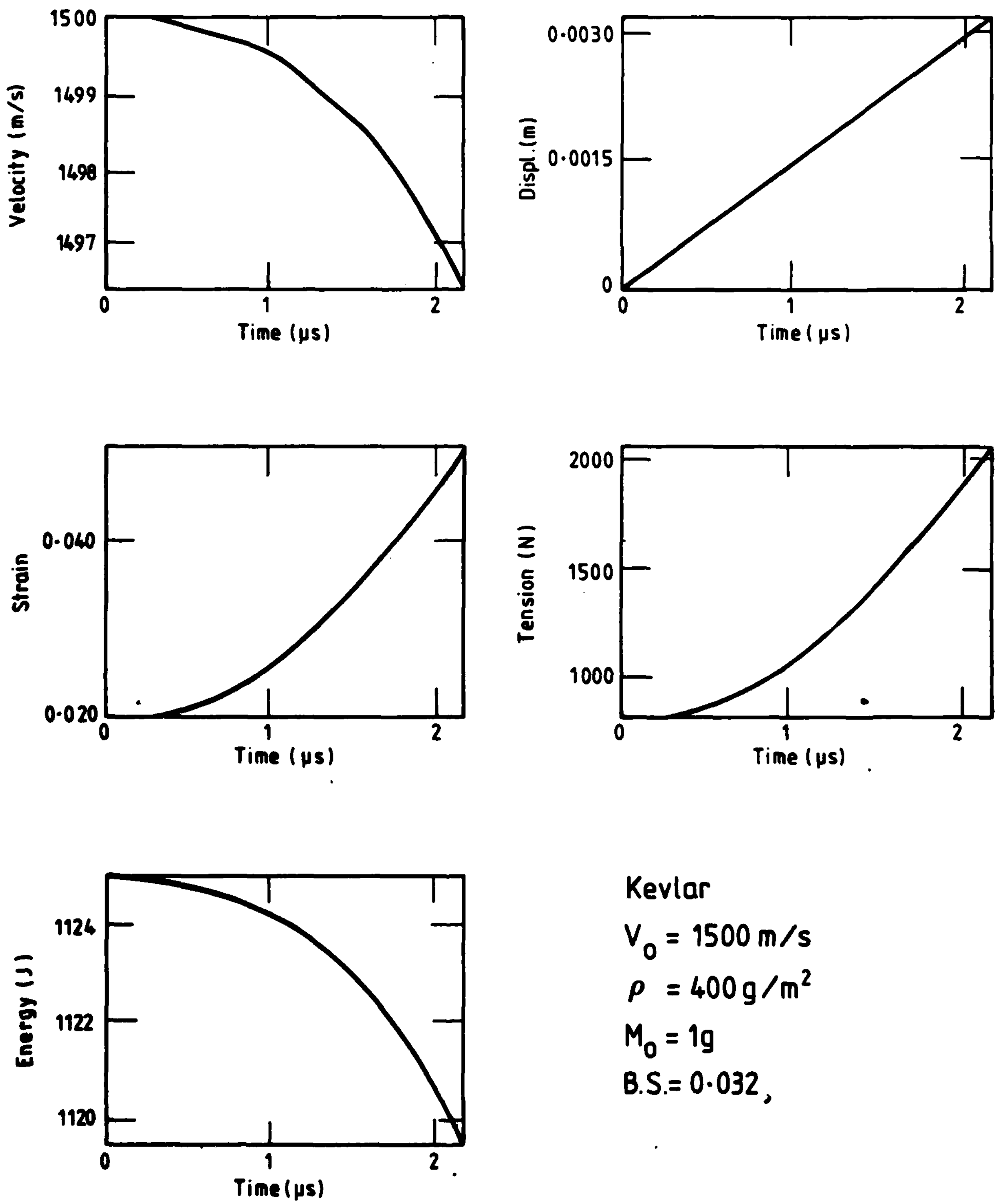


Velocity,(m/s)
495
485
0
5
Time,(μs)
Displ.(m)
0·030
0·015
0
0
5
Time,(us)
Strain
0·040
0·020
0
5
Time,(μs)
Tension,(N)
2000
1500
1000
0
5
Time,(μs)
Energy,(J)
124
122
120
118
0
5
Time,(μs)
Kevlar
$V_o$ = 500 m/s
$\rho$ = 400 g/m$^2$
$M_o$ = 1g
B.S. = 0·032

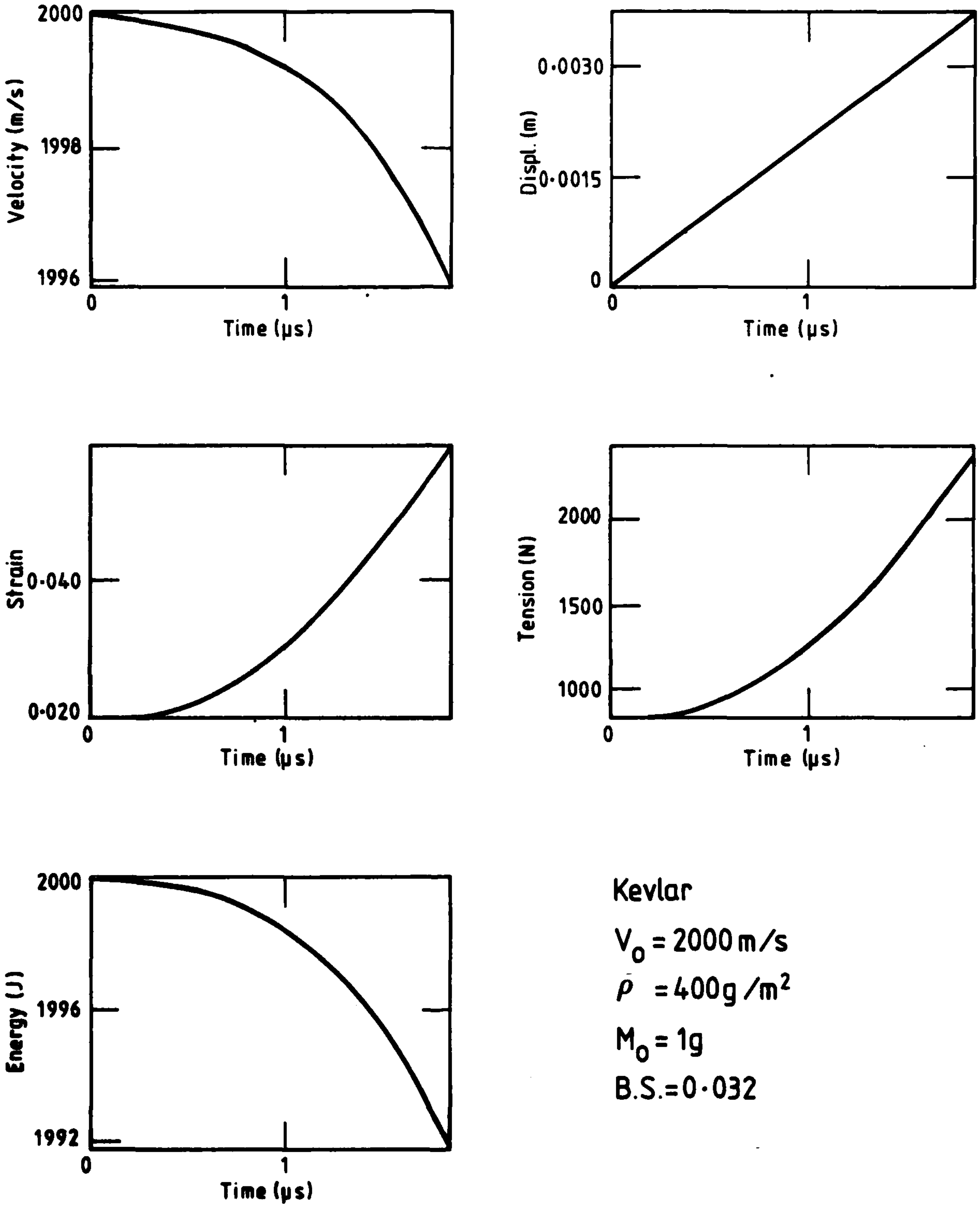

Fig. 5 (p-s)


Velocity (m/s)
1000
996
992
Time, (μs)
Displ.(m)
0·030
0·015
Strain
0·040
0·020
Tension (N)
2000
1500
1000
Energy (J)
500
496
492
0
1
2
3
Kevlar
$V_0$ = 1000 m/s
$\rho$ = 400g/m$^2$
$M_0$ = 1g
B.S. = 0·032

(q)


1500
1499
1498
1497
Velocity (m/s)
Time (μs)
0·0030
0·0015
Displ.(m)
Time (μs)
0·040
0·020
Strain
Time (μs)
2000
1500
1000
Tension (N)
Time (μs)
1124
1122
1120
Energy (J)
Time (μs)
0
1
2
Kevlar
$V_0$ = 1500 m/s
$\rho$ = 400 g/m$^2$
$M_0$ = 1g
B.S.= 0·032

(r)


2000
1998
1996
Velocity (m/s)
0
1
Time (μs)
0·0030
0·0015
0
Displ. (m)
0
1
Time (μs)
0·040
0·020
Strain
0
1
Time (μs)
2000
1500
1000
Tension (N)
0
1
Time (μs)
2000
1996
1992
Energy (J)
0
1
Time (μs)
Kevlar
$V_0 = 2000$ m/s
$\bar{\rho} = 400$ g/m$^2$
$M_0 = 1$g
B.S.=0·032

(s)

Figures 6 a, b show typical multiflash views of fabrics under impact. The photographs show a side view of impact; the projectile travels from bottom to top in each case. The minor divisions visible in figure 6a(c) are 0.5mm.

Figures 6c,d,e,f, show the variation in pyramid height with time for both nylon (figs.6a and 6b) and for Kevlar (figs.6c and 6d). These experimental results are compared to the characteristics model (figs.6c and 6e) and to the membrane model (figs.6d and 6f).

The observed failure of the fabric is shown by the termination of the experimental plot. Similarly the theoretical failure points are also shown.

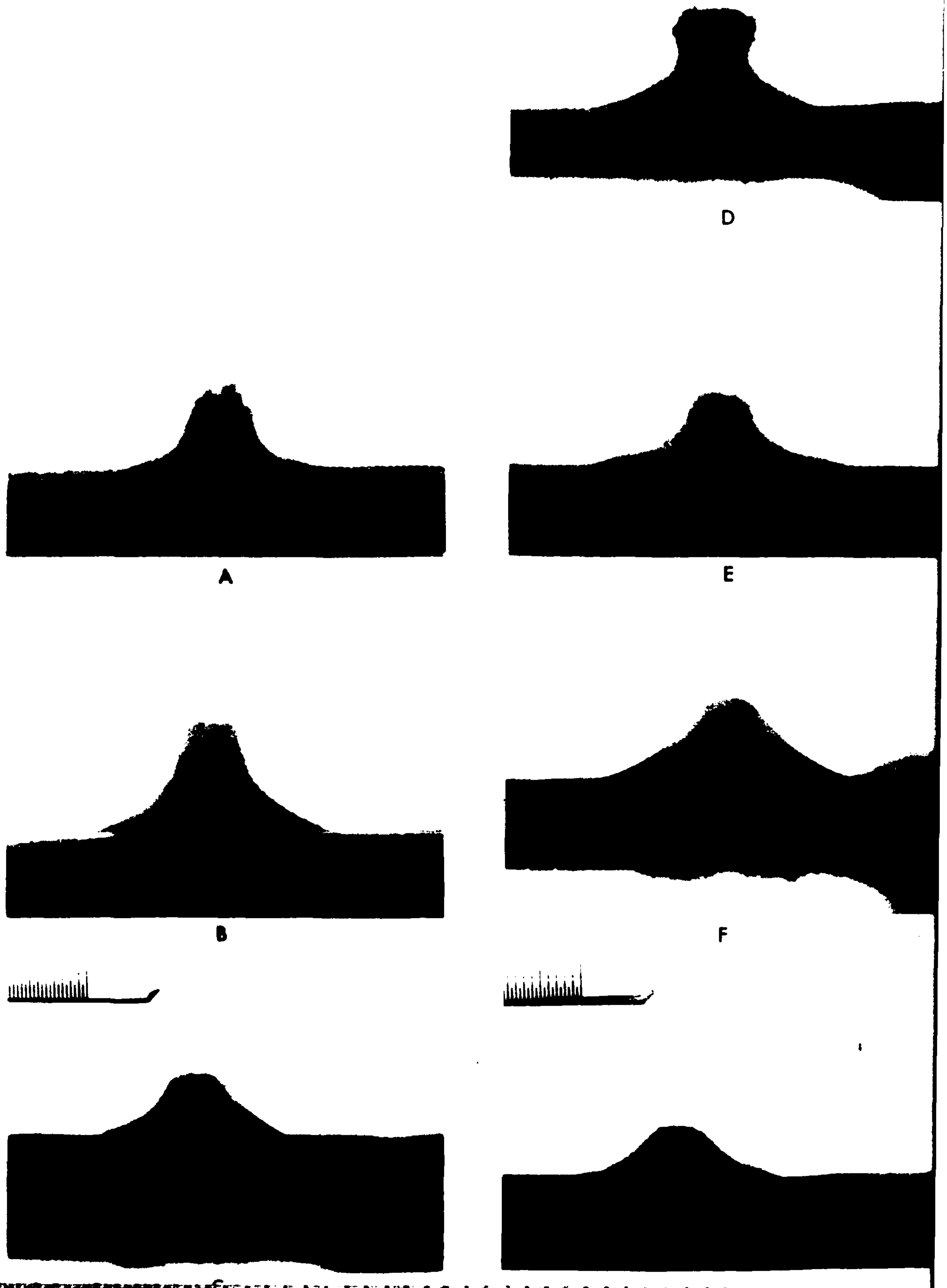
Figure 6 g, h are plots of the distance of the traverse wave from the centre of impact vs time.

Fig. 6i is a plot of pyramid height vs the traverse wave displacement. These are shown to be related linearly.

<u>Legend for Figure 6a (overleaf)</u>

Side views of impacted fabrics at 10, 20, 30 and 40 μs after impact.

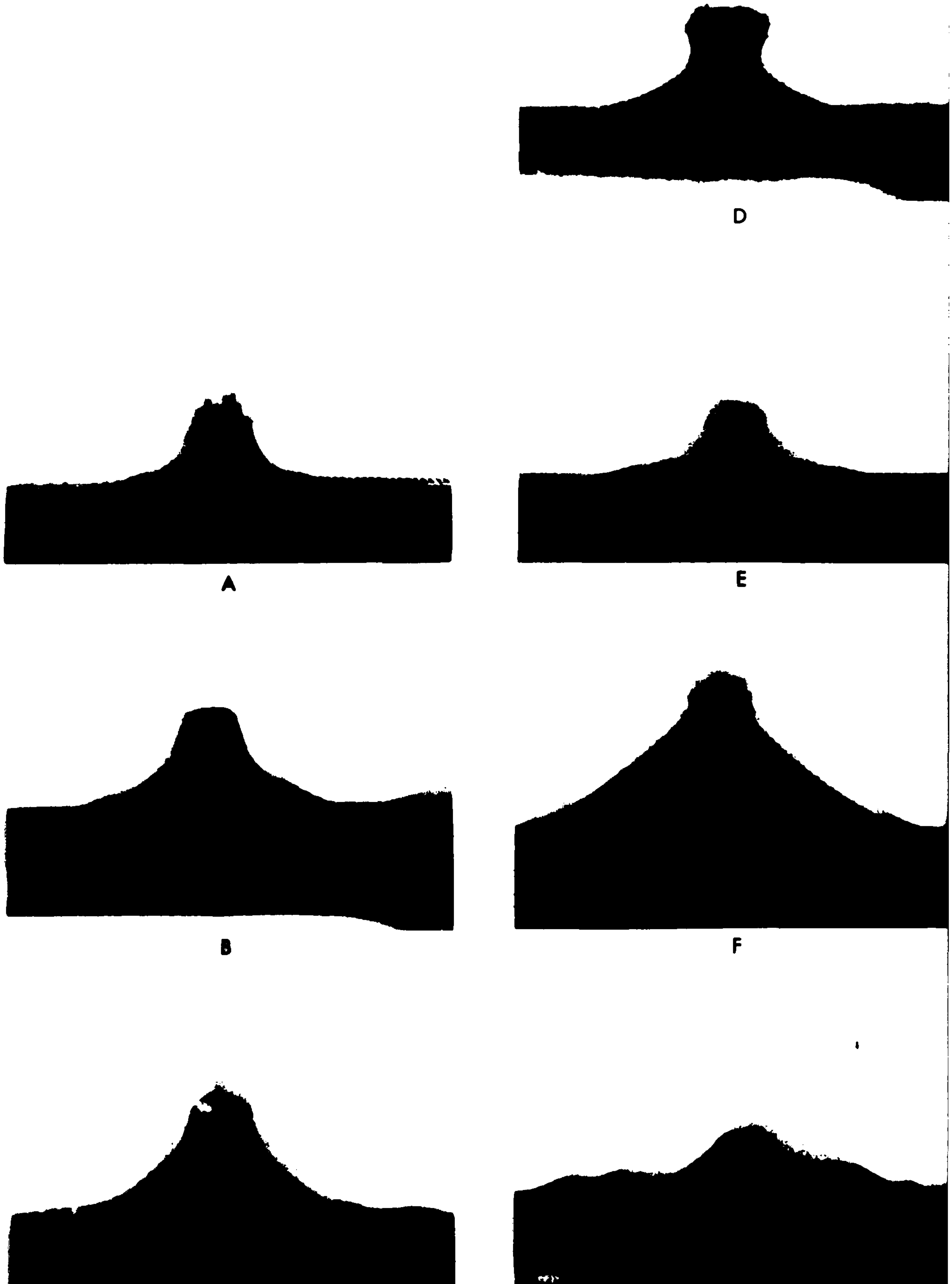
| Normal Area Density (g m-2) | Nylon | Kevlar |
|---|---|---|
| 1000 | | D |
| 2000 | A | E |
| 3000 | B | F |
| 4000 | C | G |

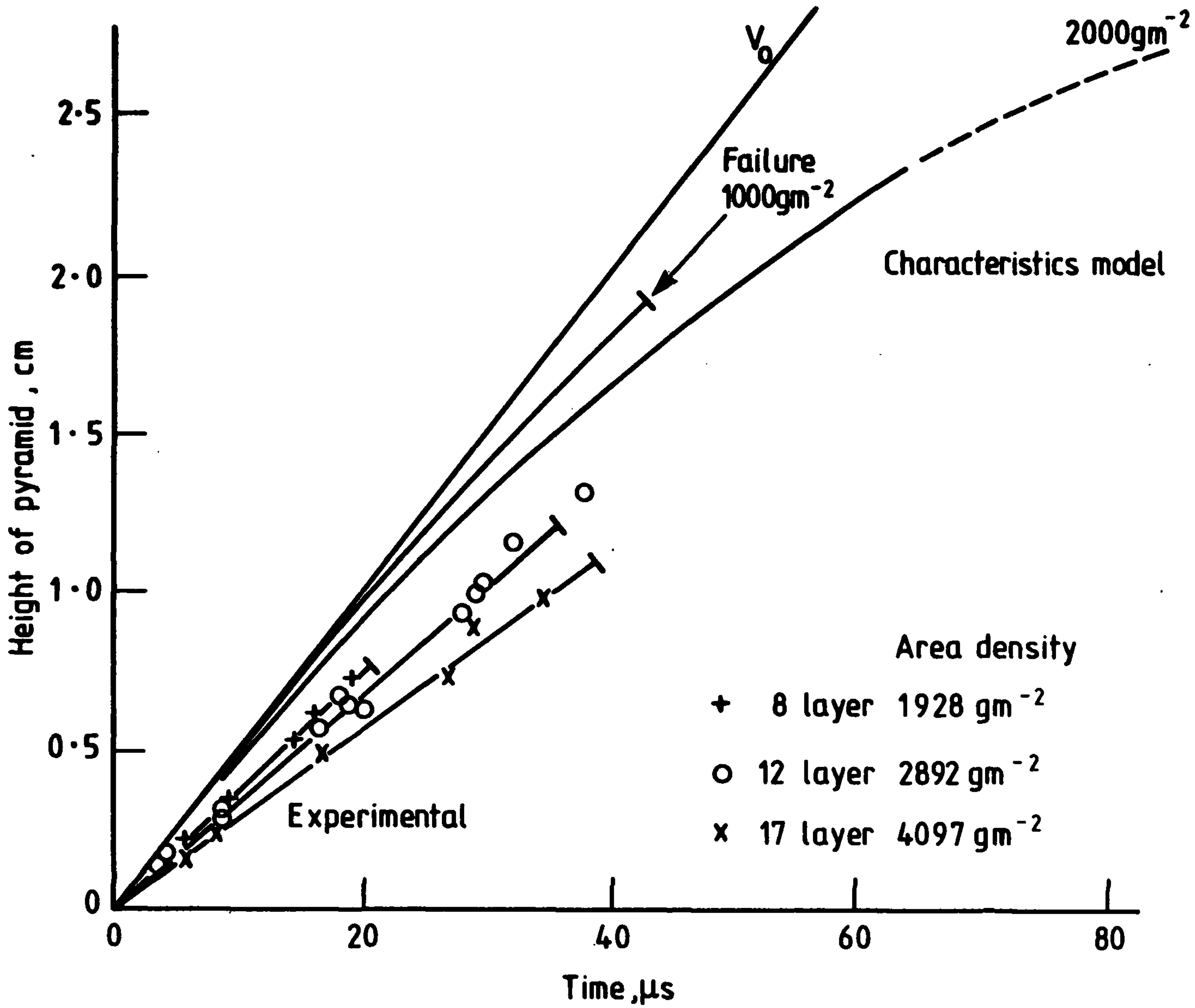

D
A
E
B
F

<u>Legend for Figure 6b (overleaf)</u>

Side views of impacted fabrics at various times after impact chosen to show penetration (the 4000 g $m^{-2}$ Kevlar was not penetrated).

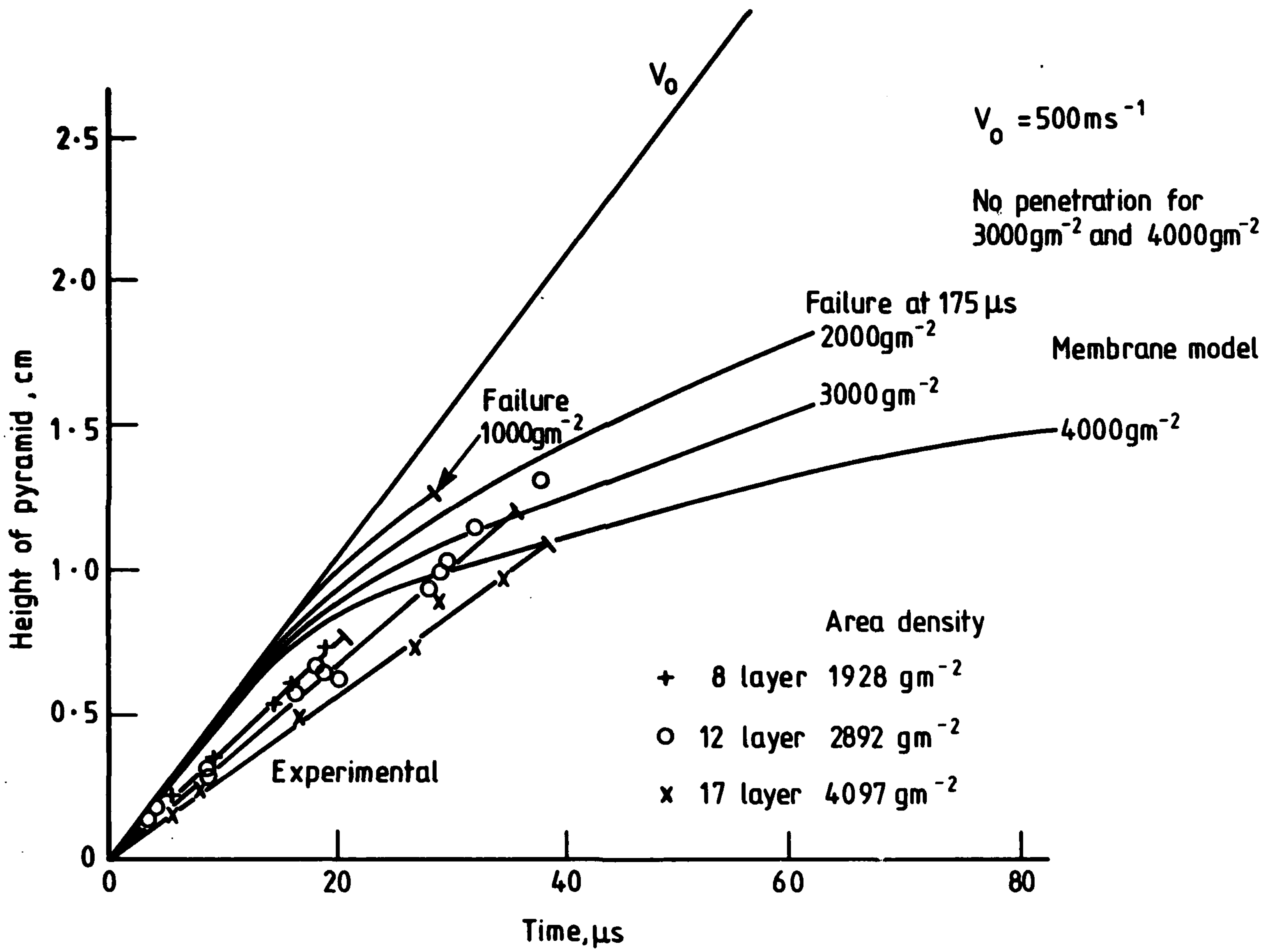
| Nominal Area Density (g $m^{-2}$) | Nylon | Kevlar |
|---|---|---|
| 1000 | | D |
| 2000 | A | E |
| 3000 | B | F |
| 4000 | C | G |


D
A
E
B
F



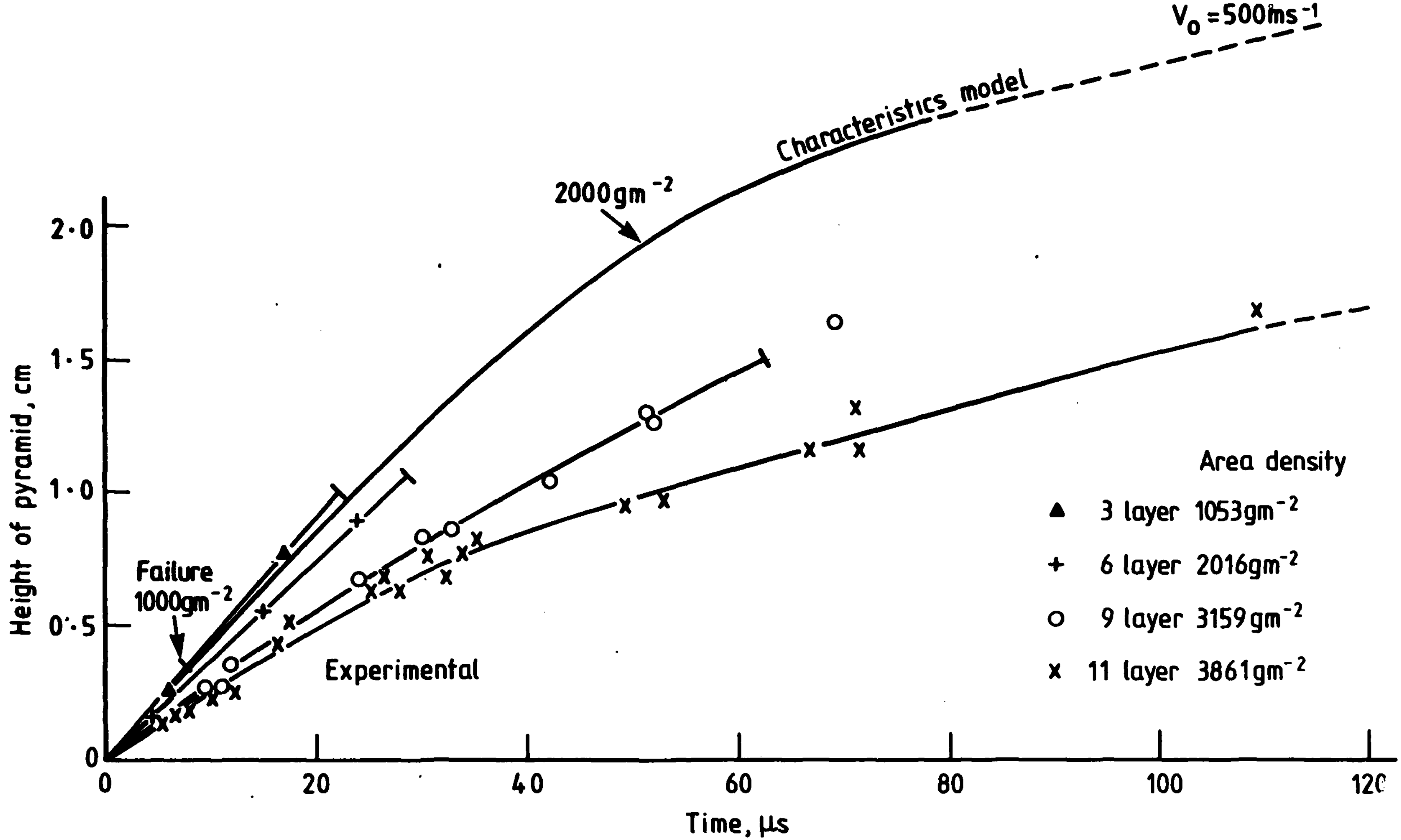

Pyramid height against time for multi-layered nylon

Fig. 6c



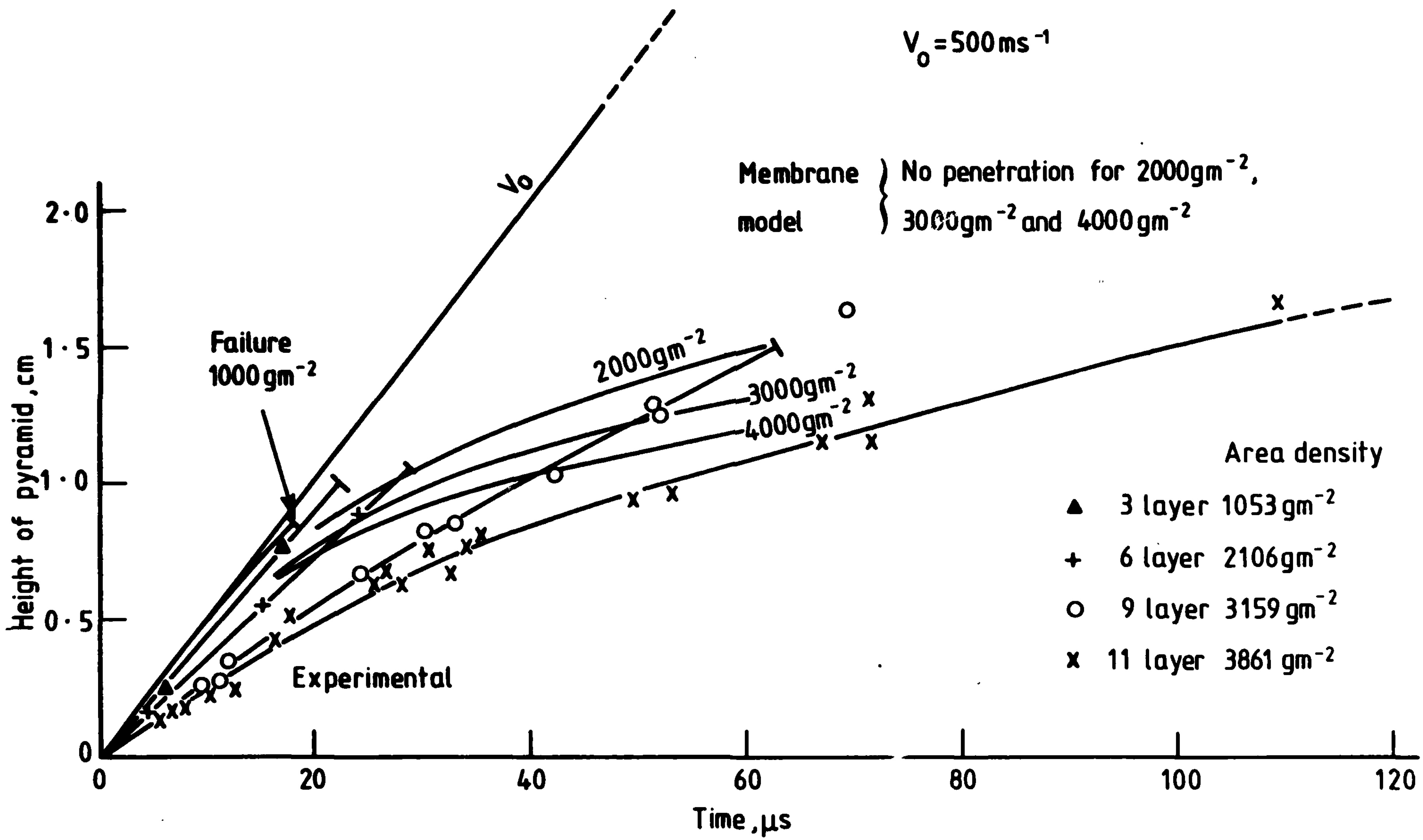

Pyramid height against time for multi-layered nylon

Fig. 6d



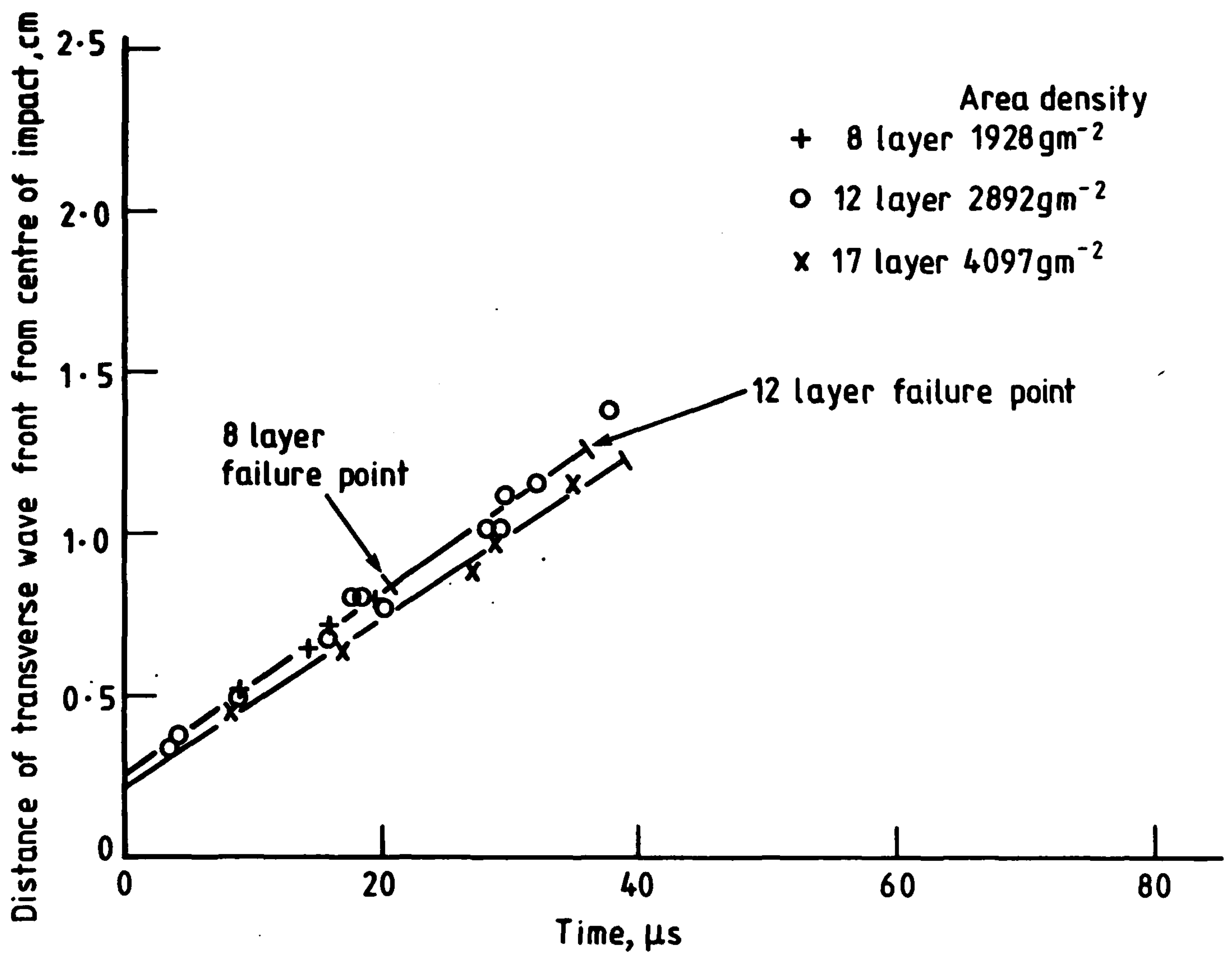

Pyramid height against time for multi-layered kevlar

Fig. 6e

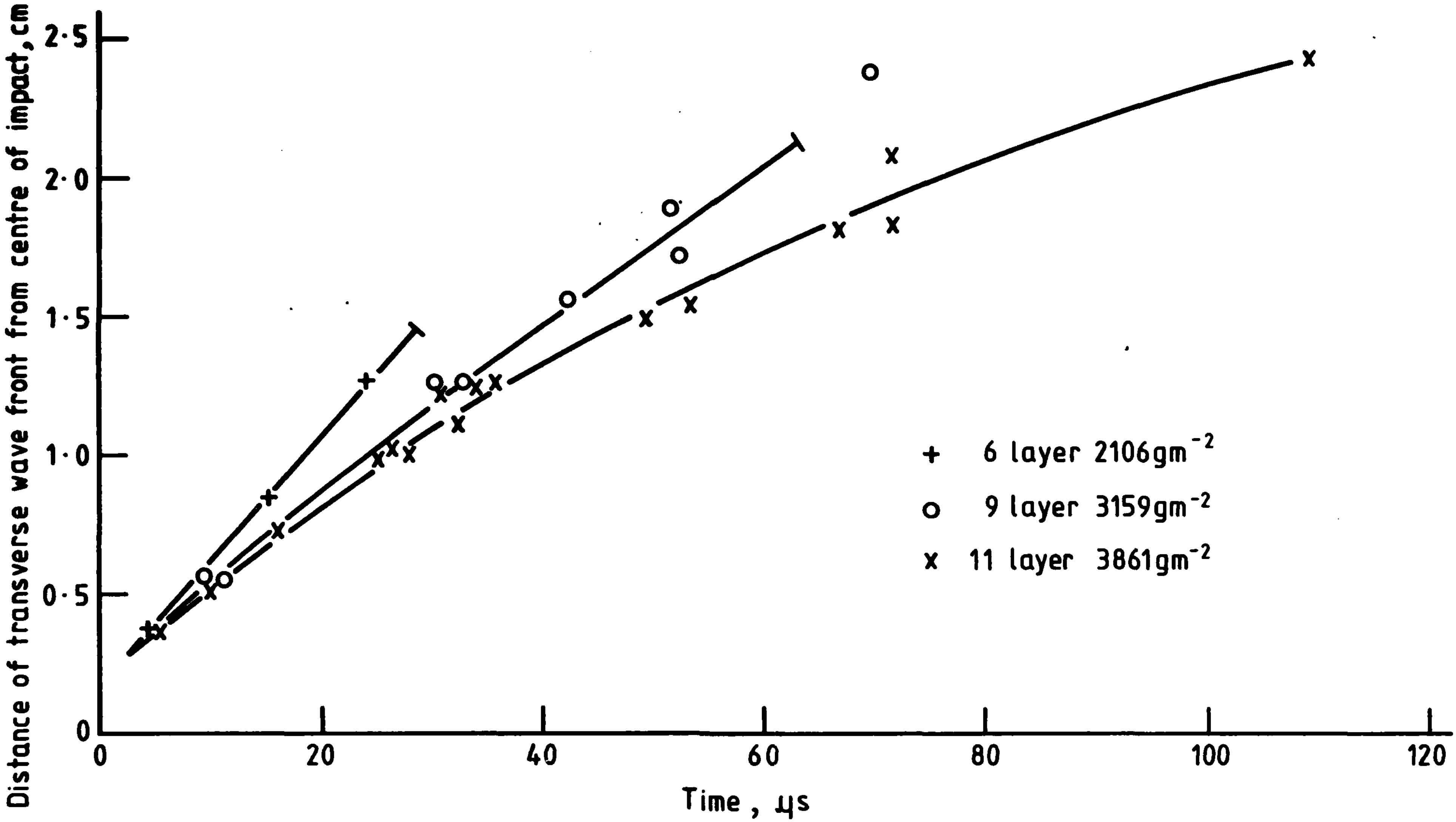



Pyramid height against time for multi-layered kevlar

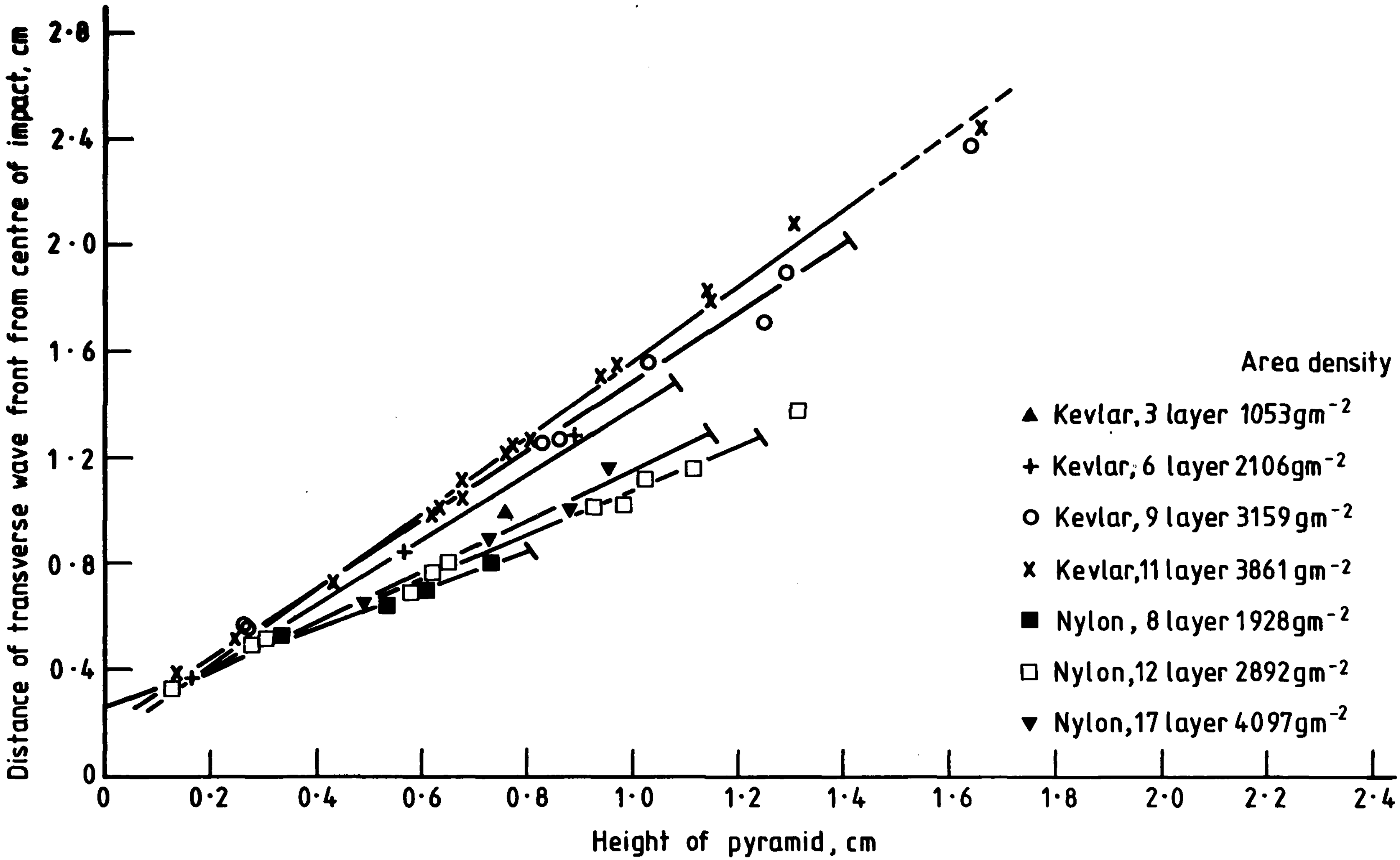
Fig. 6f




Transverse wave displacement against time for multi-layered nylon Fig.6(g)




Transverse wave displacement against time for multi-layered kevlar Fig. 6(h)




Transverse wave displacement against pyramid height Fig.6(i)

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2 Adeyefa, A. 'Mechanics of Single and Multi-layer Synthetic Textiles Subjected to High Velocity Impact' Ph.D thesis submitted to the University of Manchester Institute of Science and Technology (1982).

3 Leech, C.M., Hearle, J.W.S., and Mansell, J. 'A Variational Model for the Arrest of Projectiles by Woven Cloth and Nets' J.Text.Inst., Vol.70, Nov.1979, pp.469-477.

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## APPENDIX

Calculation of Kevlar strain so that the characteristics model would fail in order to give a resultant energy loss corresponding to that found experimentally.

| Area Density ($g\ m^{-2}$) | Energy Loss(J) (Experimental) $\Delta E$ | Projectile Energy at penetration (J) $125 - \Delta E$ | Strain |
|---|---|---|---|
| 500 | 20.1 | 105 | >0.050 |
| 1000 | 36.9 | 88.1 | *0.0375 |
| 1500 | 53.9 | 71.4 | *0.031 |
| 2000 | 70.4 | 54.6 | *0.26 highly uncertain large oscillations |

* occurs after MAXIMUM OF STRAIN

The values for 1000 and 1500 fall close to those expected. This is reflected in figure 2d where the 1000 $gm^{-2}$ and 1500 $gm^{-2}$ results for the characteristics model do agree with the excperimental results.

Again now for nylon strain (see fig.2c)

| Area Density | ($\Delta E$) | ($125 - \Delta E$) | Strain |
|---|---|---|---|
| 500 $gm^{-2}$ | 8.53 | 116.5 | 0.24 |
| 1000 | 17 | 108 | 0.205 |
| 1500 | 25.5 | 99.5 | 0.185 |
| 2000 | 34.0 | 91 | 0.170 |

Here experimental agrees with computational only at 500g $m^{-2}$. This is reflected in the above table where the breaking strain is 0.24. At higher area densities the model is grossly wrong.

The weakness of nylon could be due to either :

1. The melting of the yarns due to friction or to

2. The pushing aside of yarns by the projectile. Recent studies of damage to penetrated fabrics has shown that the number of broken yarns decreases as the projectile proceeds through the assembly.

e.g.

| LAYER | No. of Weft yarns broken |
|---|---|
| 1 | 3 |
| 2 | 3 |
| 3 | 2 |
| 4 | 2 |
| 5 | 1 |
| 6 | 1 |
| 7 | 1 |

Projectile diameter = 4.6 yarns

The effect of a yarn unloading from the projectile is as if the yarn had broken at a lower strain. This latter effect could also explain the ballistic inferiority of Kevlar compared to the Kevlar model, at high area densities (see figure 2d).

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Nylon and Kevlar textiles are examined for their performance against impact by a 1gm projectile, when subject to impact velocities up to 200 m/s. The textiles are of varying areal density, and of varying layer composition and their performance is examined theoretically and experimentally. The theoretical models have been previously developed and are the characteristic model, membrane finite element and a multilayer finite element; the experimental /Cont'd.

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